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July 30, 1991

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Subject: Contract N00164-91-C-0043

Dear Ms. Gaiser:

In accordance with our Second Quarterly Report for the above-referenced contract, we are pleased to submit an Interim Report entitled, "A Review of Thermal Enhancement Coatings for Navy Standard Electronic Module Card Rails," (CHTL-6770-3). A copy of the Report has been forwarded to the cognizant Field Contract Administration Office.

Sincerely,

Leroy S. Fletcher

Leroy S. Fletcher

Enclosure
cc: Mr. Jerry Adams/NWSCC
Mr. Martial W. Davoust/ONR-Austin
Dr. G.P. Peterson/TAMU
Ms. Kathy Ho/TAMRF

A REVIEW OF THERMAL ENHANCEMENT COATINGS FOR NAVY STANDARD ELECTRONIC MODULE CARD RAILS

CHTL-6770-3

Contract No. N00164-91-C-0043

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ABSTRACT

The reliability of Navy standard electronic modules may be improved by decreasing overall module temperature. This may be accomplished by enhancing the thermal contact conductance at the interface between the module frame guide rib and the card rail to which the module is clamped. The surface irregularities resulting from the machining or extruding of the components cause the true contact area to be much less than the apparent contact area, increasing the contact resistance. Some metallic coatings, applied to the card rail, would deform easily under load and increase the contact area and associated conductance. This investigation evaluates possible coatings and determines those most suitable for use on card rails based upon predictions using existing theories for thermal contact conductance of coated junctions.

NOMENCLATURE

a	Contact spot radius
b	Radius of heat flux channel
h	Thermal contact conductance
H	Hardness
k	Thermal conductivity
m	Combined RMS absolute asperity slope $(m_1^2 + m_2^2)^{1/2}$
N	Mean number of microcontact spots per unit area
P	Apparent contact pressure
R	Thermal contact resistance
t	Coating thickness
σ	Combined RMS roughness of both surfaces $(\sigma_1^2 + \sigma_2^2)^{1/2}$
ϕ	Constriction factor

subscripts and superscripts

an	Annular type contacts
av	Average
A	Per unit nominal area
c	Contact
f	Filler
ff	Filler-to-filler
j	Joint
M	Metal
Mf	Metal-to-Filler
MM	Metal-to-Metal
o	Oxide
OO	Oxide-to-Oxide
s	Substrate
t	Total
1,2	Refers to surfaces 1 and 2
′	Refers to coating or coated contact
-	Average

1.0 INTRODUCTION

Pursuant to the objective of enhancing the thermal contact conductance at the interface between the Navy Standard Electronic Module (SEM) formats D and E and their associated card rails, this review presents an evaluation of the most appropriate surface treatments and coating materials for the card rails.

One of the most effective means of controlling contact conductance is through the use of interstitial materials between components. The choice of interstitial material for a particular application is governed by such factors as contact pressure and temperature, environmental conditions, and of course, the degree to which it is desired to decrease or increase heat flow across the junction. Many thermal control materials are available, and Fletcher (1990) suggested that the materials could be divided into the following the major classifications:

(1) Greases and Oils
(2) Metallic Foils and Screens
(3) Composites and Cements
(4) Surface Treatments

Fletcher (1990) also identified and discussed the principal advantages and disadvantages of each group of thermal control materials. Greases and oils, although easy to apply, may leak from the joint or evaporate with time. Metallic foils are effective for increasing contact conductance. However, improper insertion of the foil into the joint can cause wrinkling of the foil and actually decrease conductance. Also, disassembly and reassembly of junctions with interstitial foils is tedious, and they generally are not suitable for use in repeated contacts. Because of these shortcomings, thermal greases and foil inserts are excluded from further consideration. Composites and cements will also be excluded since they are generally used for thermal insulation.

Surface treatments are generally used to improve contact conductance or provide thermal control. Treatments such as metallic platings, coatings, and vapor deposited films are more permanent in nature than interstitial materials and may be suitable for applications involving repeated and/or sliding contact, depending upon coating properties and clearance. Therefore, surface treatments are the best choice for many applications.

A thorough search of the literature was undertaken to identify those investigations containing data and prediction techniques for the thermal conductance of coated contacts. Three types of coating materials were identified:

(1) Metallic
(2) Oxide
(3) Anodic

In all studies, the coatings were deposited on a metallic substrate.

The results of each investigation are summarized in the literature review, and those materials suitable for thermal enhancement are identified.

2.0 LITERATURE REVIEW

There have been a number of investigations dealing with thermal contact conductance of coated surfaces. Some of these investigations do not provide enough information to permit evaluation. Those that provide complete experimental data are reviewed along with those theoretical/analytical studies which are suitable for coated surfaces.

The review is divided into two sections. The first deals with metallic coatings, the second with oxide and anodic films.

2.1 Metallic Coatings

Fried (1965) and Fried and Kelley (1965) described thermal contact conductance in the following manner. The contact heat transfer phenomenon, exclusive of the contribution of radiation, can be divided into the actual physical contact area determination and the contact heat transfer based on conduction across this actual area with and without an intervening film. The determination of the true contact area is very difficult because existing techniques are not suitable or practical. They stated that general elasticity and plasticity methods cannot be applied in most thermal contact problems for the following reasons:

(1) The microscopic irregularities do not engage each other uniformly to form contacts but do so in groups as the large scale macroscopic areas engage each other. The possibility of sliding contact cannot be excluded from this consideration.

(2) The contact intersection is neither purely elastic nor purely plastic but is elastoplastic or elastoviscous in character. Thus, as a load is applied there is a redistribution of pressure among the load-bearing asperities.

(3) The surface layers, particularly when machined and polished or when exposed and oxidized, have properties different from the underlying material.

They suggested that similar classes of materials having similar types of work history and surface finish should permit the use of statistical or semi-empirical prediction methods. Thus, although the thermal performance of a particular set of interfaces may not be specifically predicted, a method may be developed to estimate the performance of a particular class of contacts provided the surfaces are well defined.

Fried and Kelley (1965) performed contact conductance experiments using 304 stainless steel specimens coated with vapor deposited aluminum and magnesium. One trial employed aluminum coatings on both contacting surfaces, which were 1.5 and 1.9 μm (59 and 75 μin.) in thickness. The surface roughnesses were 0.6 and 1.0 μm (24 and 39 μin.). For the other trial involving the magnesium coating, a 2 μm (79 μin.) thick film was applied to one surface only. The roughnesses of the coated and uncoated surfaces were 0.6 and 0.3 μm (24 and 12 μin.), respectively. Contact pressures ranged from approximately 0.4 to 8 MPa (58 to 1160 psi). Both interstitial materials enhanced the contact conductance over that of bare joints by as much as an order of magnitude at high contact pressures. For the aluminum-coated surfaces, the values of contact conductance obtained for descending loads were less than those for ascending loads.

The basic conclusions of the investigation applicable to coated contacts are:

(1) There appears to be no significant effect of trapped or adsorbed gases on contact heat transfer.

(2) Coarsely finished surfaces appear to permit more reliable contact heat transfer predictions and provide more reproducible test data. Conversely, very finely finished surfaces (such as optically polished surfaces) result in the least reproducibility and predictability.

(3) The presence of soft metal platings substantially improves joint conductance.

(4) Statistical prediction methods appear to hold promise for the thermal performance of inexactly defined surfaces.

Mal'kov and Dobashin (1969) investigated the resistance of Kh18N9T stainless steel specimens with electroplated coatings of silver, nickel, and copper. All coatings were 25 μm

(0.001 in.) in thickness. Surface roughnesses varied from 0.85 to 1.9 μm (33 to 75 μin.), and deviations from true flatness ranged from 5 to 40 μm (0.0002 to 0.0016 in.) Apparent contact pressures ranged from 0.48 to 5.6 MPa (70 to 810 psi), and testing was performed in a vacuum. The test temperature range was 250 to 550°C (482 to 1022°F).

They found that the microgeometry of the coating surface is determined to a large extent by the microgeometry of the underlying metal surface. Although the thickness of the coatings applied in this set of experiments was 12-15 times the height of the asperities, the surface characteristics of the coatings remained practically unchanged from those of the substrate for the case of the silver coating. The surfaces of the copper and nickel coatings were somewhat rougher and smoother, respectively, then their underlying stainless steel surface.

Mal'kov and Dobashin (1969) noted that for the given pressure range, the thermal contact resistances of the coated joints were reduced by factors of 2 to 10 from the value for the uncoated contact. The resistance of specimens that were lapped after being coated became negligibly small with increasing contact pressure. Increases in surface roughness and waviness resulted in increased resistance; however, the contact resistance was less affected by pressure for increasing waviness. Coated or uncoated lapped surfaces had lower resistance than unlapped surfaces, which they attributed to the decreased roughness and waviness. The coatings became decreasingly effective with increasing waviness.

Mikic and Carnasciali (1969) developed an analysis for the thermal contact resistance of an elemental heat channel (single contact). They argued that the analysis for an elemental heat channel can be used for evaluation of contact resistance for multiple contacts between nominally flat, rough surfaces or directly applied to calculation of macroscopic constriction resistance for wavy, smooth surfaces.

They also proposed that the thermal contact resistance is inversely proportional to the thermal conductivity of the material in the disturbed region, where isothermal surfaces are not parallel to the interface. They also stated that an increase in thermal conductivity in the vicinity of the contact points will reduce the contact resistance for a fixed geometry. They noted that highly conductive platings may significantly reduce the resistance. Platings may also be used to alter the geometry of the contact for a given interfacial load due to the generally different yield strengths of the plating and substrate.

Mikic and Carnasciali (1969) further suggested that the plating of only one contacting surface should have only a limited effect on the resistance since the entire constriction on the unplated side still has to take place in a low-conductivity material. When both surfaces are plated, the combined effects of the change of thermal conductivity in the constriction region and the change in geometry of the contact are fully realized, and the contact conductance is most improved.

Their model for predicting the ratio of the coated-to-uncoated contact conductance uses as input information three ratios: t/a, a/b, k_1/k_2, where t is the plating thickness, a is the radius of the microcontact of the two plating asperities, b is the radius of the heat flux channel remote from the constriction, and k_1 and k_2 are the thermal conductivities of the plating and substrate materials, respectively. The resistance ratio for the coated-to-uncoated contacts (R_c/R) is reduced by increases in each of the three previously listed ratios.

An experimental verification of the theory was conducted by Mikic and Carnasciali (1969) using a macroscopic model of a single constriction. The plating and substrate materials were copper and 303 stainless steel, respectively. Cylinders of each material were soldered together to simulate perfect bonding of the plating to the substrate. Then a portion of each copper cylinder was turned to a smaller radius to simulate a constriction. Experiments using ratios of

a/b and t/a from 0.5 to 2.0 (k_1/k_2=23.0) yielded reductions in the resistance ratio by a factor of 10 to 20. Their experimental results demonstrated close agreement with the theory. However, no information on surface topography was provided that would allow comparison of their results to those of other investigations.

O'Callaghan et al. (1981) present a theory which predicts the optimum thickness of a metallic coating for maximum thermal contact conductance. It assumes that ideal plastic deformation occurs at the interface of a rough and smooth surface. It further assumes that the material within intersections of the surfaces (i.e., parts of the asperities protruding into the coating) has no effect on the contact conductance. They indicate that if the filler material were fully ductile it would extrude from the asperity intersections into non-contact regions and result in greater values of thermal contact conductance than the theory suggests.

The following assumptions are intrinsic to their theory:

(1) Surface asperities may be represented as right circular cones.

(2) All microcontacts regions are annular.

(3) The filler is of uniform thickness, so its presence does not alter the surface topographies.

(4) As a result of assumptions (2) and (3), the contact configuration is comprised by base-material-to-base-material circular microcontacts surrounded by concentric annuli of the filler material with additional circular microcontacts of the filler material alone.

(5) Height distributions of the asperities may be described by Gaussian probability functions.

(6) The effective thermal conductivity of a filler-to-filler contact, k_{ff}, is given by the harmonic mean of the filler and base metal conductivities.

(7) The effective thermal conductivity of an annular contact is the arithmetic mean of the base metal and filler conductivities.

They suggested that if the filler is softer than the base materials, the real contact area will be increased for a given pressure compared to the same interface without filler. They also contend that the degree of improvement depends on the ratio of the conductivities of the filler

and base materials, and the optimal filler thickness is expected to be of the order of the surface roughness.

O'Callaghan et al. (1981) conducted experiments using stainless steel (En58b) specimens with ion-deposited tin coatings ranging in thickness from approximately 3 to 106 μm (0.00012 to 0.0042 in.) Their theoretical prediction exhibited fairly good agreement with the data.

Snaith et al. (1982) identified a general criterion for determining whether a filler material of suitable thickness will decrease contact resistance:

$$H_M\, k_f \;/\; H_f\, k_M \;>\; 1$$

where H_F and H_M are the hardnesses of the filler and substrate, and k_F and k_M are the thermal conductivities of the filler and substrate.

The optimal thickness is expected to occur when filler thickness, t, is on the order of the RMS surface roughness, σ. If $t < \sigma$, resistance is reduced because of the presence of additional solid flow channels through the filler. For $t >> \sigma$, the bulk resistance of the filler tends to exceed the reduction in constriction resistance afforded by the filler. The assumptions made in developing this theory are identical to those of O'Callaghan et al. (1981).

Antonetti and Yovanovich (1985) developed a thermomechanical model for predicting the contact conductance of a nominally flat, rough surface and a metallic-coated smooth surface. A correlation for bare joints, by Yovanovich (1982), was used as the basis for this coated contact theory. The major assumptions made in formulating this theory were:

(1) Contacting surfaces are clean and in a vacuum. That is, gaseous conduction across the gaps is negligible. Radiation heat transfer is also negligible.

(2) Contacting surfaces are microscopically rough but macroscopically flat and have Gaussian height distributions.

(3) When either of the contacting surfaces is coated with a soft metal, the real pressure between the surfaces is equal to that of the "effective" hardness of the layer-substrate combination.

(4) The real contact area consists of circular, isothermal, microcontact spots which are distributed uniformly over the apparent area. When a coating is present, the contact is also assumed to be a circular spot, but now residing on the top of the coating. In other words, penetration of the harder surfaces into the coating, which undoubtedly occurs to some extent, is ignored to simplify the subsequent thermal analysis.

(5) Contact between the coating and substrate is perfect. They cited an earlier investigation by Cecco and Yovanovich (1972) which states that the resistance of a perfect joint is about two orders of magnitude smaller than the constriction resistance of the pressed contact.

(6) A coated surface has the same surface characteristics as the underlying substrate.

Their predicted contact conductance is presented in a dimensionless form that is dependent on parameters which include: surface roughness and asperity slope, apparent pressure, microhardness of the rough surface and effective microhardness of the coated smooth surface, and the effective thermal conductivity of the joint (which involves the thermal conductivities of the two contacting materials and a constriction parameter correction factor for a coated joint). They stated that the effective microhardness of the coated surface must be determined experimentally for the particular coating-substrate combination in question. Experiments were performed on silver coated nickel specimens in contact with bare nickel specimens to verify the contact conductance theory. The applied contact pressure extended over the range of 500 to 3700 kPa (72 to 540 psi), and the mean interface temperature varied from 85 to 206°C (185 to 403°F). Their results for a pressure of 2000 kPa (290 psi) were nominally within 10% of their theoretical predictions of contact conductance. The contact conductance of the coated junction was as much as an order of magnitude greater than that of the bare junction. They also noted that for a given layer thickness, the enhancement increased for smoother surfaces.

Kang et al. (1989) determined the degree to which lead, tin, and indium vapor-deposited coatings could increase the contact conductance of 6101-T6 aluminum interfaces. They used four thicknesses of each coating ranging from a few tenths of a μm to a few μm. All tests were conducted in a vacuum and over a nominal pressure range of 200 kPa (29 psi). Metrological information included average and RMS roughness, peak-to-valley height, average and RMS asperity slope, and average and maximum waviness height. They reported typical specimen surface measurements of approximately 0.7 μm (28 μin.) for RMS roughness, 0.08 for RMS asperity slope and 2.5 μm (98 μin.) for average waviness height. The average interface temperature for all tests was approximately 25°C (77°F).

They performed extensive Vickers microhardness tests of coated and uncoated specimens. Five readings at seven indenter loads were taken for each specimen tested. Coated surfaces exhibited a trend of increasing microhardness with increasing load (i.e., decreasing ratio of coating thickness to indenter penetration depth), which was also noted by Antonetti and Yovanovich (1985). Kang et al. developed analytical expressions for the effective microhardness of the three coating-substrate combinations that were analogous to that given by Antonetti and Yovanovich (1988) for a silver-coated nickel specimen. Kang et al. noted that the microhardness of the bare 6101-T6 aluminum samples increased slightly for greater indenter loads.

Kang et al. (1989) concluded that the optimal coating thicknesses were in the range of 2.0 to 3.0 μm (79 to 118 μin.) for indium, 1.5 to 2.5 μm (59 to 98 μin.) for lead, and 0.2 to 0.5 μm (8 to 20 μin.) for tin. They reported maximum coated-to-uncoated contact conductance ratios of approximately 7, 4, and 1.5 for indium, lead, and tin, respectively, and suggested that the coating hardness appears to be the most significant factor in ranking the effectiveness of a coating. They further noted that the conductance enhancement provided by a coating of a given thickness was greatest at low contact pressures, decreasing significantly with increases in contact pressure.

They reasoned that as pressure was initially increased, the growth in contact area of the coated joints was much greater than for the bare joints due to the softness of the coating. They went on to state that as the pressure was steadily increased, the rapid growth in contact area was reduced by the contact between substrate asperities which had penetrated the coating material. Finally, they concluded that the reduction in the contact area growth rate resulted in a reduction in the thermal contact conductance enhancement. Kang et al. (1989) also observed that the optimal coating thickness decreased as pressure was increased.

Chung et al. (1990) studied the effects on contact conductance of ion-vapor-deposited coatings of aluminum, lead, and indium on 6061-T6 aluminum. They employed two coating thicknesses, 25.4 and 50.8 μm (0.001 and 0.002 in.), and two surface roughnesses, 1.6 and 3.2 μm (63 and 126 μin.). Two-surface coatings (i.e., both surfaces of a contact pair were coated with a combined coating thickness of 25.4 or 50.8 μm) were also investigated. Thermal conductance enhancement varied from 0 to 500 percent of the uncoated value depending on the surface characteristics. Four nominal contact pressures from 100 to 500 kPa (14 to 72 psi) were used.

The ratios of coated-to-uncoated contact conductance for the rougher substrates showed greater improvements. This was attributed to the fact that a rougher substrate will penetrate a soft coating more deeply, thereby increasing contact area and contact conductance. For the smaller substrate roughness, 1.6 μm (63 μin.), pressure had little effect on the conductance ratio with the exception that the thicker indium coating exhibited a peak conductance at 175 kPa (25 psi). Also, for aluminum and lead coatings, the coated-to-uncoated conductance ratios for the two coating thicknesses showed little difference, while the conductance ratios for indium increased slightly for the thicker coating.

For the larger substrate roughness, 3.2 μm (126 μin.), the conductance ratio increased with pressure for aluminum and lead coatings and was generally slightly less for the thicker coating than for the thinner coating. Interfaces coated with indium exhibited an opposite trend of higher conductance ratios for the thicker coating, and contact pressures between 175 and 275 kPa (25 and 40 psi) provided the greatest enhancement of conductance. Also, for a given coating material and total coating thickness, two-surface coatings generally provided greater increases in contact conductance than one-surface coatings.

The enhancement of thermal contact conductance varied from 150 to 500, 0 to 250, and 0 to 100 percent increases for indium, aluminum, and lead, respectively. Chung et al. (1990) observed that the differences between the conductance ratios of two-surface and one-surface coatings were dependent on the coating material involved. Lead coatings showed no significant differences, whereas two-surface coatings of aluminum and indium displayed significantly increased conductance over one surface values. They noted that in general, for a given coating thickness the enhancement of conductance increases with surface roughness, provided the thickness of the coating is many times greater than the value of surface roughness.

Chung et al. (1991) examined pure copper and copper-carbon mixtures (transitional buffering interfaces, TBI) applied to both contacting surfaces of 6061-T651 Al. They employed four aluminum surface roughnesses ranging from 0.17 μm to 3.55 μm (6.8 to 142 μin.). Two coating thicknesses, 0.19 and 0.24 μm (7 and 9 μin.) for the copper coatings and 0.25 and 0.45 μm (10 and 18 μin.) for the Cu/C coatings, were tested for each of the four surface roughnesses. The coating process involves plasma-enhanced deposition onto cold surfaces of either conducting (metallic) or non-conducting (nonmetallic) base material. They claimed that TBI coatings provide excellent contact conductance and long life under repeated loads.

Pure copper yielded contact conductance values 1.09 to 1.31 times those for copper and carbon phase mixtures over a pressure range of 125 to 500 kPa (18 to 72 psi). They stated that pure copper coating is more thermally conductive than a Cu/C coating because of the low thermal conductivity and high hardness of carbon.

They assumed that load cycling increased contact conductance by successively plastically deforming the surfaces. There were also hysteresis effects, i.e., the unloading conductance was greater than loading conductance for a given pressure. Blasted rough, bare surfaces had higher conductances than polished surfaces by a factor of from 1.3 to 2.6 due to the larger area of contact spots of the former. They also noted that the most significant improvement in conductance, as a result of the application of coatings, was obtained for turned surfaces (as opposed to polished or blasted surfaces) for which the root-mean-square (rms) roughness was approximately equal to the coating thickness. Coating thicknesses beyond this led to decreased conductance. Also, coatings much thinner than the surface roughness values did not improve conductance.

2.2 Oxide and Anodized Coatings

Yip (1974) developed a prediction for the contact resistance of oxidized metal surfaces. These oxides form as a result of exposure to the atmosphere, fresh or sea-water, or soil. He stated that oxides are much less ductile than most light metals, and their presence decreases the actual contact area. He suggested that contact conductance is further reduced by the generally poor thermal conductivity of oxides.

The expression for estimating contact resistance includes as variables: surface roughness, asperity slope, nondimensional oxide thickness, the ratios of apparent pressure to substrate metal hardness and oxide-to-metal hardness, and the thermal conductivities of the metal and its oxide.

The theory predicts a one-hundred fold increase in contact resistance for aluminum with a total oxide thickness approximately equal to the surface roughness for a non-dimensional stress of 10^{-3}, which is the ratio of the apparent pressure to the metal hardness.

Yip noted that the oxidation film thickness of aluminum alloys varies from 0.003 to 0.3 μm (0.12 to 12 μin.) when such metals are exposed to air at various humidities. Magnesium and its alloys exhibit a build-up of magnesium hydroxide at a rate of 0.01 μm (0.4 μin.) per year when exposed to humid air. He stated that the roughness of machined surfaces may range from 0.025 to 6.5 μm (0.98 to 256 μin.). Thus, it was suggested that the contact resistance of aluminum alloys may vary by a factor of 100 over the stated range of surface finishes and severity of oxidation.

He conducted experiments using specimens of 6061-T6 aluminum alloy with one of two rms average surface roughnesses, 1.5 and 6.6 μm (59 and 260 μin.), and an assumed oxide thickness of 0.075 μm (3 μin.). Theory and data agreed quite well for this assumed oxide thickness. The contact resistance increased by a factor of nine for a pair of smoother surfaces with roughnesses of 1.5 μm (59 μin.) and by a factor of two for a pair of surfaces with roughnesses of 6.6 μm (260 μin.). Yip's theory could not be explicitly proven accurate due to the lack of knowledge of actual oxide film thicknesses.

Mian et al. (1979) examined the contact resistance of oxide films on samples of mild steel (EN3B). They tested specimens that were lapped flat then sandblasted to a roughness of 0.08 μm (3.3 μin.). One contacting surface was oxidized to obtain a film thickness of 0.35 μm (14 μn.). They employed a form of the Arrenhius equation was used to estimate the growth of oxide films for various temperatures and oxidation periods.

The data, when plotted with additional data for different oxidized EN3B specimens obtained from colleagues (Al-Astrabadi et al., 1980), indicated that the thermal contact resistance

decreased with increasing load and surface roughness. Mian et al. suggested that the common slope of the linear-resistance-versus-pressure traces was suggested to be the result of ideal plastic deformation of the surface irregularities. They also attributed the observance of a slight hysteresis upon unloading to plastic deformation. The contact resistance was doubled when the ratio of total oxide film-thickness-to-surface-roughness was approximately equal to four, but increases in the ratio beyond this value did not significantly increase the contact resistance. The film thickness, rather than the roughness, was the dominant variable affecting the resistance. They correlated the entire population of data and demonstrated that it agreed reasonably well with Yip's theory.

Mian et al. (1979) identified factors that affect contact resistance. These include constriction and dilation of heat flow in oxide films, the shapes of the microcontacts as dictated by the history of the surfaces, the isotropy of the surface roughness, and the degree of waviness. They also proposed that knowledge of the manner in which oxide films rupture, the local yielding regions, and the fracture stresses are needed for a comprehensive understanding of the behavior of oxidized contacts. The authors contend that although the film does fracture, it is still present and probably affects the contact resistance.

Al-Astrabadi, et al. (1980) developed a theoretical prediction for the contact resistance of oxidized, nominally flat, randomly rough metallic surfaces. The assumptions regarding the nature of the microcontacts are analogous to those later described by O'Callaghan, et al. (1981). The filler material for the former case was an oxide film, whereas in the latter investigation it was replaced by a metallic coating. Al-Astrabadi et al. noted that an oxide is, in general, harder and less ductile than its parent metal. Thus, they concluded that the formation of oxides tends to reduce the true metal-to-metal contact for freshly assembled joints, resulting in increased thermal contact resistance.

Al-Astrabadi et al. (1980) contended that the resistance of a metal-to-metal joint between clean surfaces, assembled in a vacuum and under constant heat flux and loading, should decrease when exposed to an oxidizing atmosphere. This is due to the growth of oxide around the contacting asperities leading to enhanced annular oxide-to-oxide contacts as well as additional newly formed oxide-to-oxide bridges. However, they also stated that resistance is seen to increase with oxide film growth because of several factors.

(1) The contact is seldom subjected to a constant load and heat flux.

(2) Such mechanical and thermal fluctuations result in intermittent contact behavior allowing the growth of oxides to disrupt the metallic contact bridges.

(3) The accumulation of oxide in the non-contact regions could force the surfaces apart, breaking the metallic bridges.

(4) Oxide and contaminant formation induces passive transient behavior, encouraging factors (2) and (3) above.

They conducted experiments to verify the theory using mild steel (EN3B) specimens with surface roughnesses ranging from approximately 0.12 to 2.0 μm (4.7 to 79 μin.), asperity slopes between 0.04 and 0.19 radians, and oxide film thicknesses of 0.055 to 0.118 μm (2.2 to 4.6 μin.). They noted that oxidation of the surfaces had a minimal effect on their topography, and the distribution of asperity heights was nearly Gaussian. However, they cautioned that this observation was only valid for thin oxide films. Heavily oxidized surfaces exhibited a five-fold increase in roughness over the unoxidized condition and displayed skewed height distributions. The theory agreed reasonably well with the data for the range of surface parameters examined.

The authors further noted that when coated surfaces are pressed together, the contact is different from bare surfaces under identical conditions. They stated that the following three ratios influence the contact resistance: the ratio of coating to substrate hardness, the ratio of coating to substrate thermal conductivity, and the ratio of coating thickness to surface roughness. They

postulated that if the coating is much thicker than the roughness, then the resistance increases with increasing coating thickness. Provided that the coating thickness is on the order of or less than the roughness, the resistance will decrease if the coating is much softer than the substrate.

Peterson and Fletcher (1991) conducted an experimental investigation of the thermal contact conductance of anodized coatings. Seven anodized samples of 6061-T6 aluminum with coating thicknesses ranging from 60.9 to 163.8 μm (0.0024 to 0.0065 in.) were tested in contact with a single bare sample. Surface roughness ranged from 0.30 to 5.33 μm (12 to 210 μin.), while asperity slopes varied from 0.08 to 0.25. All surfaces were flat to within approximately 1 μm (39 μin.). Both the overall joint conductance between the anodized and bare surface and the bulk conductance of the anodic coating increased with increasing contact pressure and decreased with increasing coating thickness.

The authors described the basic methods in applying anodic surface treatments and other types of coatings. Anodized coatings result from an oxidation process at the surface of a material. Although anodized surfaces are mechanically similar to electroplated or vapor-deposited coatings, the anodized coatings are created by chemical conversion of the outer layers of a material, whereas the other two processes involve the bonding of a substance to the substrate. The oxidized surface is an integral part of the material and has excellent adherence.

Their conclusions indicated that for very smooth, untreated surfaces, slight increases in the roughness cause moderate increases in contact conductance. The overall joint conductance was more sensitive to variations in pressure for the thinner coatings than for the thicker coatings. They explained this as being due to variations in the effective microhardness of the surfaces. They proposed that for very thin anodized layers, the effective microhardness of the interface results from a combination of the uncoated aluminum surface, the relatively hard oxide, and the aluminum substrate. As the thickness of the anodized surface increases, the uncoated surface

asperities do not penetrate the anodized coating, and the effective microhardness results only form a combination of the uncoated aluminum surface and the anodized surface.

Using their experimental data, the authors developed an empirical, dimensionless expression that related the overall joint conductance to the coating thickness, the surface roughness, the interfacial pressure, and the thermophysical properties of the aluminum substrate.

3.0 EVALUATION OF THEORETICAL PREDICTIONS

This section is devoted to describing how the various theories for predicting contact conductance compare to the available data. The prediction (or predictions) that best models the existing data is used to determine the level of contact conductance enhancement afforded by the potential rail coating materials. These materials are listed in Table 1, and discussed in more detail in this section. First, the adequacy of the prediction technique must be ascertained.

The descriptions and comparisons of the various theories and data given below refer frequently to Figs. 1a and 1b. These figures illustrate four prediction techniques and data from ten investigations on the thermal contact conductance of metallic junctions with metallic or oxide (including anodic) interstitial coatings. All data and prediction technique included in Figs. 1a and 1b have been reduced to the same dimensionless groupings as those employed by Antonetti and Yovanovich (1985), since this prediction technique proved to be most useful for reducing all of the information to an equivalent form. It should be noted that all the prediction techniques incorporate Bessel functions into the computation of constriction factors for characterizing the contact. These often involve simultaneous solution of several algebraic or integral equations. However, the analysis in Antonetti and Yovanovich (1988) also contains a table of constriction factors that are listed in terms of topographical (i.e., metrological), thermophysical, and loading information on the contact that is readily, though tediously, calculable. This later work illustrates the application of their 1985 investigation to different coatings and substrates. The predictions of Antonetti and Yovanovich (1985) and O'Callaghan et al. (1981) explicitly apply to metallic coatings, whereas those of Al-Astrabadi et al. (1980) and Yip (1974) are intended for oxide films.

The predictive technique in Antonetti and Yovanovich (1985) utilizes the mean asperity slope, m, a surface parameter not found in all ten investigations on contact conductance from

which data has been extracted. However, Antonetti and Yovanovich (1985, 1988), Kang et al. (1989), Al-Astrabadi et al. (1980), Peterson and Fletcher (1990), Yip (1974), and O'Callagahan et al. (1981) did provide measurements of mean asperity slope. Analysis of the metrological information revealed a relationship between RMS asperity slope and RMS roughness, which is described by the expression:

$$m \approx \sqrt{\frac{\sigma}{100}}$$

This relationship was used in reducing data from those investigations lacking asperity slope measurements to the nondimensional form given by Antonetti and Yovanovich (1985). This expression is accurate to within approximately ±50% for all but the data of O'Callaghan et al. (1981). The measurement asperity slopes of O'Callaghan et al. are considerably smaller than those predicted by the slope equation.

Translation of the other three prediction techniques, those of O'Callaghan et al.(1981), Al-Astrabadi et al. (1980), and Yip (1974), to the nondimensional form found in Antonetti and Yovanovich (1985), resulted in a family or group of parallel lines for each theory. Since the prediction lines for each theory were not widely separated, the average trace of each group is plotted in the appropriate figure (1a or 1b). As evident in both figures, the predictions lie quite closely to each other, and they tend to define an upper bound to the data. Also, as expected, each theory closely approximates its associated data. The predictive expressions from the four theories described above, as well as the expression for anodized surfaces from Peterson and Fletcher (1990), are listed in Appendix A.

The two theories that apply to metallic coatings, those of O'Callaghan et al. (1981) and Antonetti and Yovanovich (1985), are almost precisely colinear, although they extend over the low and high pressure regimes, respectively. Although the two theories for metallic coatings are

accurate for their corresponding data, they both perform rather poorly for the majority of the data on such contacts extracted from other investigations: Chung et al. (1991), Fried and Kelley (1965), Kang (1989), and Mal'kov and Dobashin (1969). The two predictions overestimate the contact conductance by as much as a factor of 100. These discrepancies may be due in part to the fact that all of the theories implicitly assume that the contacting surfaces are perfectly flat, so they cannot account for the significant flatness deviations (waviness) reported in some of the other studies. As the waviness of a surface increases, its contact area decreases, thereby reducing the contact conductance. For example, specimens used by Mal'kov and Dobashin (1969) exhibited surface waviness measurements from 5 to as great as 40 μm (0.0002 to 0.0016 in.). This last value is approximately 20 times larger than its associated roughness. This wide range of waviness may be the cause of the considerable scatter of the results from their experiments seen in Fig. 1a. Fried and Kelley (1965) listed the maximum flatness deviation as 3.8 μm (150 μin.). Although, this value is approximately four times the associated rms surface roughness, it is unlikely that this alone could have caused the very low dimensionless conductances (nearly two orders of magnitude less than the theories) calculated for this set of experiments. These large variations may suggest the existence of some important and, as of yet, unrecognized parameter. Chung et al. (1991) did not provide explicit values of waviness. However, some of the specimens they studied had turned surfaces, which usually exhibit significant deviations from flatness. Kang (1989) listed waviness heights typically equal to 2.5 μm (98 μin.) for the turned aluminum surfaces examined.

The anodized 6101-T6 aluminum and nickel plated C11000 copper SEM frames have specified flatness deviations of 50 and 250 μm (0.002 and 0.010 in.), respectively. Thus, for the reasons described above, the contact conductance of these frames to the A356-T61 aluminum card rails should be significantly less than that predicted by the theory of Antonetti and

Yovanovich (1985).

Since the theory in Antonetti and Yovanovich (1985) is presented in the most tractable form for calculations, it is used here to estimate the contact conductance provided by the possible coating materials listed in Table 1. This prediction describes the upper bound of contact conductance, since it was developed for flat surfaces. The estimated contact conductances of coated contacts determined using this prediction, will not be representative of real machined or ground surfaces (which exhibit considerable waviness) unless corrected by some appropriate factor to account for this waviness. No theory has been proven adequate for quantitatively evaluating the effect of surface waviness. Consequently, the estimated ratios of coated to uncoated contact conductance listed in Table 2 and illustrated in Fig. 2 are no doubt inflated. The value of these computed ratios is in the fact that they allow the various candidate coatings to be qualitatively compared and ranked in order of expected thermal performance.

The predictions for contacts containing interstitial oxide films, shown in Fig. 1b, although accurate for oxide films, somewhat overestimate the contact conductance of junctions with anodic coatings. Peterson and Fletcher (1991) conducted experiments on 6061-T6 aluminum with anodized coating thicknesses varying from 61 to 164 μm (0.0024 to 0.0065 inch) and surface roughnesses from 0.3 to 5.3 μm (12 to 212 μin.) in contact with bare 6061-T6. The specimens had flatness deviations on the order of 1 μm (39 μin.) or less. Since the descriptions of the 6101-T6 SEM frames do not stipulate the exact anodized coating thickness, it is assumed to be 50 μm (0.002 inch) as instructed in MIL-A-8625E (1988). The roughness of the aluminum 6101-T6 frames is specified to be 0.6 μm (24 μin.), and the maximum allowable flatness deviation is 50 μm (0.002 in.). Thus, apart from surface flatness, these two contact systems are quite similar since the thermal conductivities and hardnesses of the aluminum alloys considered do not differ greatly. As with metallic contacts, increased deviations from flatness cause reductions in the

contact area and, consequently, the contact conductance. Therefore, the values of conductance obtained in Peterson and Fletcher (1991) should be greater than those of the presently employed anodized 6101-T6 to uncoated A356-T61 junctions.

4.0 SELECTION OF CANDIDATE COATING MATERIALS

A number of materials have been used as coatings for controlling the thermal contact conductance of pressed contacts. This section describes in detail the selection of those coatings that may best improve the contact conductance of the SEM/card rail interface.

4.1 Coating Materials

As explained by Fletcher (1990), of the four basic types of interstitial materials, only surface treatments and coatings are deemed suitable for microelectronic applications. Coatings may be polymeric, ceramic, composite, metallic, nonmetallic, or oxidic in nature. Although polymeric coatings are typically resistant to deterioration in a marine environment, and may improve conductance if impregnated with metal particles, they generally only provide moderate enhancement. Ceramics and oxides are almost invariably insulative. Composites generally exhibit the same performance as polymers, as they are usually comprised mainly of polymeric resins. Metallic coatings are typically the most highly thermally conductive materials and may afford the greatest improvement in thermal contact conductance. Thus, consideration of possible coating materials is limited primarily to metals.

One noteworthy, potentially highly conductive nonmetallic coating material is carbon. It exists in two main allotropic forms, graphite and diamond. Graphite has a thermal conductivity of 1950 W/m-K in directions parallel to the layers of atoms although its thermal conductivity is only 5.7 w/mK perpendicular to the layers. This is approximately five times that of silver, the most conductive metal. However, graphite is probably too soft and brittle to remain intact in sliding or clamped contacts. Chemical vapor-deposited (CVD) diamond coatings are also highly conductive (1000-1300 W/m-K), as determined by Herb et al. (1989). Diamond is extremely

hard and impervious to environmental corrosion. Diamond also has a high thermal conductivity, and is extremely effective as an electrical insulator. At present the effect of CVD diamond coatings on contact conductance is unknown, and additional research is necessary to determine the performance of diamond films for both static and sliding thermal enhancement applications.

4.2 Coating Requirements for Maximum Contact Conductance

Criteria that are considered most important for enhancement of the thermal contact conductance of the frame-rail interface have been evaluated. Some investigators, such as O'Callaghan et al. (1981) and Snaith et al. (1982), suggest that the ideal coating material possesses a large ratio of thermal conductivity to hardness. They contend that coatings of low hardness deform readily under load, flow around the asperities, and thereby increase the contact area. High values of thermal conductivity tend to alleviate the constriction resistance through the reduced areas of the microcontacts, and this coating property is considered by Mikic and Carnasciali (1969) to be highly important. A number of metals with high ratios of thermal conductivity-to-hardness are listed in Table 1 for comparison.

4.3 Survey of Metallic Elements

Since metals are the type of coating material thought to be most appropriate for SEM/card rail applications, an assay of all metallic elements has been made to justify the selection of those elements considered as candidate coatings. Those selected are listed in Tables 1 and 2. Properties of the metals were taken from a number of sources, including: Tabor (1951), the Metals Handbook (1990), Touloukian and Ho (1972, 1976), Hultgren et al. (1973), Westbrook and Conrad (1973), Ho (1974), Weast, (ed) (1974), Smith (1981), Richman (1967), Brick et al. (1971), and Flinn and Trojan (1981). A summary of the performance characteristics is provided

in Table 2.

The elements in the periodic table, shown in Appendix B, are arranged according to their electronic configurations, which give rise to many of their properties. Therefore, it would seem logical to sort through the metals group by group, a group being those elements with similar valence or outer shell electron configurations, to determine those which best suit the requirements of a conductance-enhancing coating.

The first two columns of the periodic table, except for hydrogen, contain the alkali metals with valence numbers of one or two. These are typically highly reactive. All but two, beryllium and magnesium, may be summarily excluded from consideration because they are either poisonous, radioactive, available in insufficient supply, or react vigorously or even explosively when exposed to moisture or ignite spontaneously when exposed to air. Beryllium, although it is employed where lightness and stiffness are needed and does resist oxidation in air, is toxic. Although Beryllium has a high thermal conductivity, it is toxic and is very hard with a Brinell Hardness (BHN) of 97. Magnesium tarnishes slightly when exposed to air and ignites when heated. This combination of disadvantages makes magnesium an unlikely choice. However, since it is used in a number of applications, it is included in the group of candidate coatings.

To the right of the alkali metals are the rare-earth or lanthanide series of metals, and below them are the actinide series. Lanthanum, the first of the rare-earths, oxidizes rapidly in air and exhibits low to moderate toxicity. Next is cerium, which oxidizes very readily in moist air and may ignite if scratched. Praseodymium, though somewhat more stable than lanthanium or cerium, develops a green oxide coating in air which spalls off, thereby exposing more of the metal. Neodymium quickly tarnishes in air, its oxide also spalls off, and it has low to moderate acute toxicity. Promethium is extremely rare, it does not exist naturally on earth, and must be

synthesized at great expense. Samarium, though reasonably stable in air at room temperature, ignites when heated above 150°C and is also possibly toxic. Europium is about as hard as lead, is the most reactive metal of this series, and quickly oxidizes in air. As with other rare-earth metals, except for lanthanium, europium ignites in air at 150 to 180°C. Gadolinium is relatively stable in dry air, but in moist air it tarnishes with the formation of a loosely adhering oxide film that spalls off. Terbium is reasonably stable in air and is soft and ductile, however, it is very expensive and possibly toxic. Dysprosium is soft and relatively stable in air at room temperature, rapidly oxidizes in moist air and at elevated temperature, and possibly exhibits low toxicity. Erbium is fairly stable in air and does not oxidize as rapidly as some of the other rare-earth metals. Thulium is reasonably stable in air but will oxidize when exposed to moisture. It is expensive and has low to moderately acute toxicity. Ytterbium, while fairly stable, oxidizes in air and moisture and has low acute toxicity. The last rare-earth, lutetium, is stable in air but very expensive and also has low toxicity.

Below the rare-earth metals are the actinides. The first in this series, actinium, is highly radioactive. Its chemical behavior is similar to the rare-earths, particularly lanthanum. Thorium is soft and very ductile, however, it is a radiation hazard and should be stored and handled in areas with good ventilation. Protactinium is a dangerous toxin and is very expensive. Uranium and its compounds are highly toxic, both chemically and radiologically. Neptunium, found only in trace quantities in nature, is chemically reactive and very expensive. The remainder of the transuranium elements (those to the right of uranium) are radiological poisons. They are absorbed by bone marrow, and trace quantities may destroy the body's ability to generate blood corpuscles.

To the right of the rare-earth metals in the periodic table are the ten columns of transition elements. The subject of their applicability is discussed in more detail, as they are not

radioactive and are generally less reactive than the alkali or rare-earth metals.

In the first column of the ten columns of transition elements are scandium and yttrium. Their properties resemble those of the rare-earth elements. Scandium is relatively soft, oxidizes slightly in air, is expensive, and may also be toxic. Yttrium is less expensive than scandium and is relatively stable in air in bulk form.

The second column is composed of titanium, zirconium, and hafnium. All have excellent resistance to seawater corrosion. Titanium is too hard (BHN 200) to be useful as a coating.

Vanadium, niobium, and tantalum comprise the third column. Vanadium is moderately hard and ductile and resistant to salt water. Niobium is slightly harder but still ductile. It begins to oxidize above 200 C. Tantalum is almost completely inert below 150°C and is relatively hard (BHN 60). All are considered because of their desirable low reactivity.

Chromium, the uppermost element of the fourth column is extremely resistant to corrosion and is usually quite hard, even in the annealed state (BHN 100). It is included in consideration because it is widely used as a protective plating. Molybdenum and tungsten are too hard and brittle for this application.

As for the fifth column, manganese is extremely hard (BHN 300) and brittle, so it not considered. Technetium does not naturally exist, is very expensive, and is radioactive. Rhenium, is corrosion and wear resistant, but too hard to be useful.

The top element in the sixth column, iron, is moderately hard (BHN 70) and oxidizes rapidly in moist air. The next two, ruthenium and osmium, are extremely hard (BHN 220 and 400, respectively) and are stable in air at room temperature. The oxides of the latter two are highly toxic and unsuitable for microelectronic interfaces.

The seventh column of the transition elements contains cobalt, rhodium, and iridium. All are extremely oxidation resistant. Cobalt is moderately hard (BHN 48) in the annealed state and

may be worth consideration. Rhodium is very hard (BHN 135), but, since it is sometimes employed as a plating, it is listed as a candidate material. Iridium is even harder (BHN 170) than rhodium, so it is unlikely to improve conductance.

In the eighth column are nickel, palladium, and platinum. All are noble metals and are used to differing extents as platings. Thus, all are evaluated in terms of their applicability to this project. Nickel is fairly hard (BHN 75). Palladium and platinum are markedly softer but expensive.

The ninth column is occupied by copper, silver, and gold. These are the most highly conductive metals and are relatively soft, making them attractive possibilities. Copper and silver tarnish slightly in air. Gold has the unique property among the metals that its oxide is unstable. Therefore, gold surfaces will remain bright indefinitely.

Zinc, cadmium, and mercury comprise the tenth and last column of the transition metals. Cadmium is soft and also toxic but used extensively in electroplating. Thus, it is considered. Mercury is, of course, highly poisonous and liquid at room temperature, making it unsuitable. Zinc is fairly soft but highly reactive. It is frequently used as a plating, so it is included in the present analysis.

To the right of the transition metals are those elements that become increasingly more like metalloids and nonmetals with increasing proximity to the noble gases. Beginning with the column under boron, the first metal encountered is aluminum, which is quite soft and highly conductive, making it worthy of attention. However, aluminum does form an oxide scale in air. Gallium, next below aluminum, has an insufficiently high melting point, 30°C (86°F). Indium is extremely soft and more resistant to atmospheric corrosion than silver. There is evidence that it has a low level of toxicity, but this is considered minor and is effectively dealt with by exercising normal hygiene. Thallium, at the bottom of this column, is very soft. It also forms

a heavy oxide if left in air and is poisonous, even when only in contact with the skin.

The first metalloid below carbon is germanium. It is crystalline and brittle, therefore unsuitable. Tin is next. It is very soft and resistant to sea water. Last in this column is lead, which is also very soft and resistant to corrosion. A lead carbonate-hydroxide forms on lead in the presence of moisture and carbon dioxide, resulting in a white deposit on the surface. Care must be exercised in handling lead as it is a cumulative poison.

Arsenic is the first metalloid below nitrogen. It is very hard (BHN 147) and brittle, tarnishes in air, and is poisonous. Underneath arsenic is antimony, which is an extremely brittle metal with a flaky, crystalline texture. It does not react with air at room temperature, but burns when heated. Antimony is also toxic. At the bottom this column is bismuth. It is quite soft, though poorly conductive. It burns when heated sufficiently in air. Since it is so soft (BHN 11) it is evaluated as a coating, despite its disadvantages.

Below oxygen and sulfur is selenium, a nonmetal which resembles sulfur in its various forms and compounds and has a very low thermal conductivity. Although elemental selenium is considered almost nontoxic, hydrogen selenide is extremely poisonous. Tellurium is a semiconductor and is brittle and probably toxic. Polonium is dangerously radioactive.

In all, 20 metallic elements were chosen for evaluation of their ability to enhance the contact conductance of the frame-card rail interface. Their selection was based on loosely defined requirements of low hardness, high thermal conductivity, excellent corrosion resistance, or a combination of these properties.

4.4 Coating Thicknesses

Reasons for the specification of coating thicknesses for the candidate metals listed in Table 2 are described below. Coating thicknesses which are of the same order as the combined

rms surface roughness have been demonstrated to be optimal by O'Callaghan (1981). Existing data on the various coating materials was utilized in selecting the precise thickness of each coating to be used in calculations of contact conductance. Kang (1989) demonstrated that the optimal coating thicknesses for indium, lead, and tin on substrates of 6061-T6 aluminum were 2.5, 2.0, and 0.5 μm (98, 79, and 20 μin.), respectively. The surfaces roughness of the nominally flat specimens investigated by Kang (1989) was typically 0.7 μm (28 μin.), which is nearly equal to that specified for the 6101-T6 aluminum and copper frames. Since a surface roughness of 0.6 μm (24 μin.) is prescribed for the frame materials, it is here assumed that this would be an appropriate roughness for the A356-T61 aluminum card rails. Thus, because the optimal coating thickness is assumed to be dependent on the roughness, and because the roughness of the specimens used by Kang is approximately equal to that assumed to be appropriate for the rails, the optimal thicknesses of the indium and lead coatings given above are used for the present purposes. A tin coating thickness of 2 μm (79μin.) is used instead of 0.5 μm (20μin.) to maintain uniformity. It seems odd that the optimal tin coating thickness should be greatly different from the optimal lead coating thickness, since they have essentially the same hardness.

Antonetti and Yovanovich (1988) reported the ideal thickness of a silver coating on an aluminum substrate to be approximately 20 μm (0.0008 in.) for a combined rms roughness for both surfaces of 4 μm (157 μin.), yielding a ratio of coating thickness-to-roughness of five. Thus, for a combined rms roughness of 0.85 μm (33 μin.) for the frame-rail combination, the optimal silver coating thickness should be approximately 4 μm (157 μin.). The same coating thickness is employed in calculations involving materials that are similar in hardness (BHN from 25 to 40 kg/mm^2) to silver (e.g., gold, copper, magnesium, etc.). Aluminum and bismuth are intermediate in hardness to the very soft coatings (indium, tin, and lead) and the group containing silver, gold, copper, magnesium, platinum, etc. Thus, an intermediate value of thickness, 3 μm

(120 μin.), is used in computations for the aluminum and bismuth coatings. The remaining metals in Table 1 with hardness values greater than BHN 40 are assigned coating thicknesses of 5 μm (197 μin.) for calculations of contact conductance, since it appears that the optimal coating thickness increases with increasing hardness.

5.0 PREDICTIONS OF CANDIDATE MATERIAL PERFORMANCE

The performance of the various coating materials has been evaluated in terms of their applications to SEM card rails. Note that Table 2 lists two coated-to-uncoated contact conductance ratios for each material. These are for the minimum and maximum contact pressures, 173 and 865 kPa (25 and 125 psi), respectively, prescribed for the frame-card rail interface. The contact conductance information provided in Navy RFP N00164-90-R-0565 lists a contact resistance of 0.189°C/W for a contact area of 0.00159 m^2 (2.46 $in.^2$) without specifying the associated contact temperature and pressure. The corresponding area-independent contact conductance is 3334 W/m^2K. This value is used as the uncoated conductance in calculating the conductance ratios.

As listed in Table 2 and illustrated in Fig. 2, the three very soft coatings (indium, tin, and lead) provide the greatest estimated increases in thermal contact conductance. However, according to Table 1 of MIL-STD-889B (1976), lead is susceptible to galvanic corrosion in a marine environment, when in contact with the nickel plating of the C11000 copper frames. Thus, lead is excluded from consideration. Aluminum, magnesium, zinc, and cadmium coatings should improve the contact conductance. But, as indicated in MIL-STD-889B, these metals are also incompatible with the nickel plating. Bismuth is not listed in the galvanic series included in Table 2 of MIL-STD-889B, but, judging from its position to the right of lead (i.e., generally more active due to a sometimes higher valence number than lead), it is probably also incompatible.

Silver, gold, copper, palladium, platinum, rhodium, chromium, cobalt, tantalum, and, of course, nickel are all compatible with the nickel plating of the C11000 copper card rails. Although not listed in MIL-STD-889B, vanadium and niobium are both probably compatible with the nickel plating because they are almost completely surrounded in the periodic chart by metals

that are compatible with nickel (i.e., chromium, molybdenum, tungsten, tantalum, and titanium). These harder metals (e.g., silver, gold, etc.) do not afford such large estimated improvements in contact conductance as do indium and tin.

MIL-STD-889B does not provide information on the comparability of metals in contact with anodized aluminum surfaces, such as those of the 6101-T6 aluminum frames. It is likely that dissimilarities in electric potential of the proposed coatings with the anodized 6101-T6 aluminum are less severe than with the nickel-coated C11000, because the low electrical conductivity of the anodized coating should greatly impede galvanic corrosion of the card rail coating. Nevertheless, in order to be conservative in evaluating the proposed coatings, the observations made for contacts involving the nickel-coated C11000 copper are assumed to hold for contacts involving the anodized 6101-T6 aluminum.

6.0 CONCLUSIONS

Although estimates indicate that indium is expected to provide the greatest enhancement of thermal contact conductance, its poor shear strength makes it susceptible to being worn from the A356-T61 rail surfaces with repeated removal and insertion of the SEM frames. Tin is expected to be second in terms of increasing contact conductance. However, tin platings, when mechanically or thermally stressed, have been found to form "whiskers" in electronic components. Also, at temperatures below -18°C (0°F) tin platings deteriorate into a powder.

Of the remaining metals that are compatible with the nickel plated copper frame, silver, gold, and copper are expected to provide far greater increases in contact conductance than the rest. Since copper forms a light oxide and its thermal conductance is calculated to be slightly less than that of gold or silver, copper would likely be supplanted by one of the other two. Silver also tarnishes slightly but its cost is a small fraction of that of gold. Both silver and gold are readily plated or deposited onto surfaces, and they are excellent choices for the rail coating.

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TABLE 1: Thermophysical Properties of Candidate Coating Materials

Material	Atomic Symbol	Brinnel Hardness (BHN) (kg/mm^2)	Thermal Conductivity (W/mK)	Thermal Expansion Coefficient (μm/mK)	Melting Point (C)	Mol. Weight	Density (g/cm^3)	Comments[1]
Indium	In	1	23.9	32.1	156.6	114.8	7.3	Inert, low toxicity
Lead	Pb	4	35.3	29.	327.5	207.2	11.34	Inert, cumul. toxin
Tin	Sn	5	66.6	20.	232	118.7	7.31	Inert
Aluminum	Al	16	237.	25.	660.4	27.0	2.71	Oxidizes
Silver	Ag	25	429.	19.	961.9	107.9	10.5	Oxidizes slightly
Gold	Au	30	317.	14.2	1064.4	197.0	19.3	Inert
Copper	Cu	35	401.	16.6	1083.4	63.5	8.9	Oxidizes slightly
Cadmium	Cd	23	96.8	30.	320.9	112.4	8.6	Oxidizes, toxic
Zinc	Zn	30	116.	35.	419.5	65.4	7.14	Oxidizes
Magnesium	Mg	30	156.	25.	648.8	24.3	1.74	Oxidizes
Palladium	Pd	40	71.8	11.8	1552	106.4	12.0	Inert
Platinum	Pt	40	71.6	9.	1772	195.1	21.45	Inert
Cobalt	Co	48	99.2	13.8	1490	58.9	8.9	Inert
Bismuth	Bi	11	7.86	13.	271.3	209.0	9.80	Oxidizes
Rhodium	Rh	135	150.	8.	1966	102.9	12.5	Inert
Chromium	Cr	100	93.7	6.	1903	52.0	7.1	Inert
Nickel	Ni	75	90.7	13.	1453	58.7	8.9	Inert
Niobium	Nb	80	53.7	80.4	1950	92.9	8.4	Inert
Tantalum	Ta	60	57.5	6.5	2977	181.0	16.6	Inert
Vanadium	V	72	30.7	8.3	1730	50.9	5.96	Inert

[1] Reactivity in air, level of toxicity.

TABLE 2: Estimated Thermal Contact Conductance of Candidate Coatings

Coating Material	Atomic Symbol	Rank	Contact Pressure[1] (psi)	Estimated Thermal Contact Conductance[2] (W/m^2-K)	Coated/ Uncoated Conductance Ratio[3]	Coating Thickness (μm)	Comments[4]
Indium	In	1	25/125	163,000/756,000	48.9 /227	2.5	Comp.
Lead	Pb	2	25/125	59,700/250,000	17.9 / 75.0	2.0	Inc.
Tin	Sn	3	25/125	54,600/232,000	16.4 / 69.6	2.0	Comp.
Aluminum	Al	4	25/125	31,500/146,000	9.45/ 43.8	3.0	Inc.
Silver	Ag	5	25/125	23,200/107,000	6.96/ 32.1	4.0	Comp.
Gold	Au	6	25/125	18,600/ 85,300	5.58/ 25.6	4.0	Comp.
Copper	Cu	7	25/125	16,800/ 77,600	5.04/ 23.3	4.0	Comp.
Cadmium	Cd	8	25/125	16,300/ 75,300	4.89/ 22.6	4.0	Inc.
Zinc	Zn	9	25/125	13,600/ 62,500	4.08/ 18.8	4.0	Inc.
Magnesium	Mg	10	25/125	11,900/ 54,800	3.57/ 16.4	4.0	Inc.
Palladium	Pd	11	25/125	9,390/ 43,400	2.82/ 13.0	4.0	Comp.
Platinum	Pt	12	25/125	9,120/ 42,200	2.74/ 12.7	4.0	Comp.
Cobalt	Co	13	25/125	8,300/ 38,400	2.49/ 11.5	5.0	Comp.
Bismuth	Bi	14	25/125	8,140/ 37,500	2.44/ 11.2	3.0	Probably Inc.
Rhodium	Rh	15	25/125	6,520/ 30,300	1.96/ 9.08	5.0	Comp.
Chromium	Cr	16	25/125	5,240/ 24,300	1.57/ 7.30	5.0	Comp.
Nickel	Ni	17	25/125	5,170/ 24,000	1.55/ 7.20	5.0	Comp.
Niobium	Nb	18	25/125	4,120/ 19,100	1.24/ 5.74	5.0	Probably Comp.
Tantalum	Ta	19	25/125	3,940/ 18,200	1.18/ 5.44	5.0	Comp.
Vanadium	V	20	25/125	3,300/ 15,300	0.99/ 4.59	5.0	Probably Comp.

[1] Minimum/maximum allowable contact pressures for SEM-guide rail interface.
[2] Calculated using theoretical prediction of Antonetti and Yovanovich (1985) for nominally flat surfaces.
SEM surface topography used in calculations: combined rms roughness of both surfaces, 0.85 um; rms asperity slope, 0.11.
Flatness deviation (.002 in. for aluminum surfaces, .010 in. for nickel-plated copper) not used in calculations.
[3] Thermal contact conductance of uncoated contact is 3334 W/m^2-K.
[4] Comp./Inc. denotes compatability or incompatability with Ni plating on C11000 card rail as per MIL-STD-889B (1976).

Figure 1A. Dimensionless Contact Conductance vs. Relative Pressure for Metals with Metallic Coatings

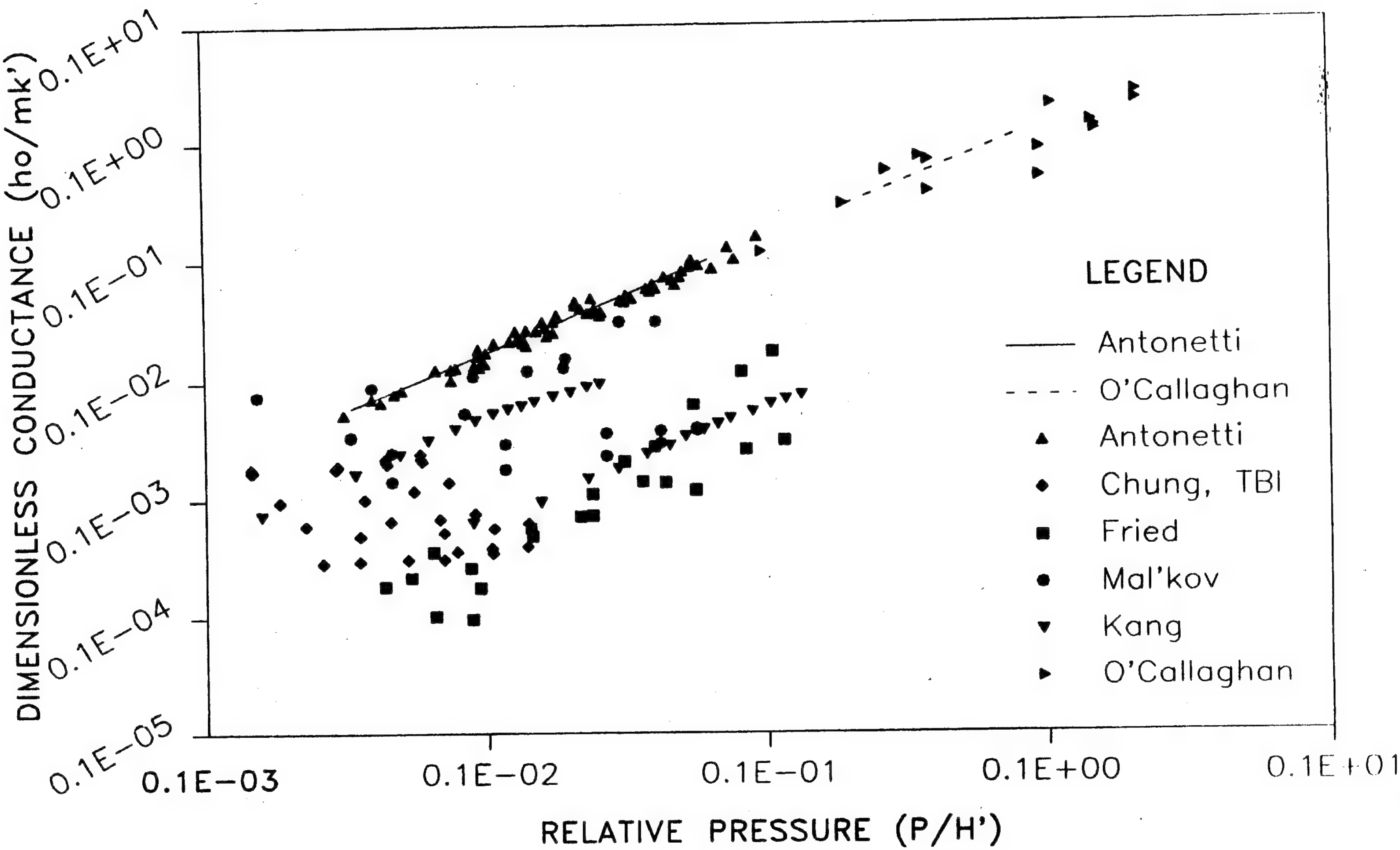


Figure 1B. Dimensionless Contact Conductance vs. Relative Pressure for Metals with Oxide and Anodic Coatings

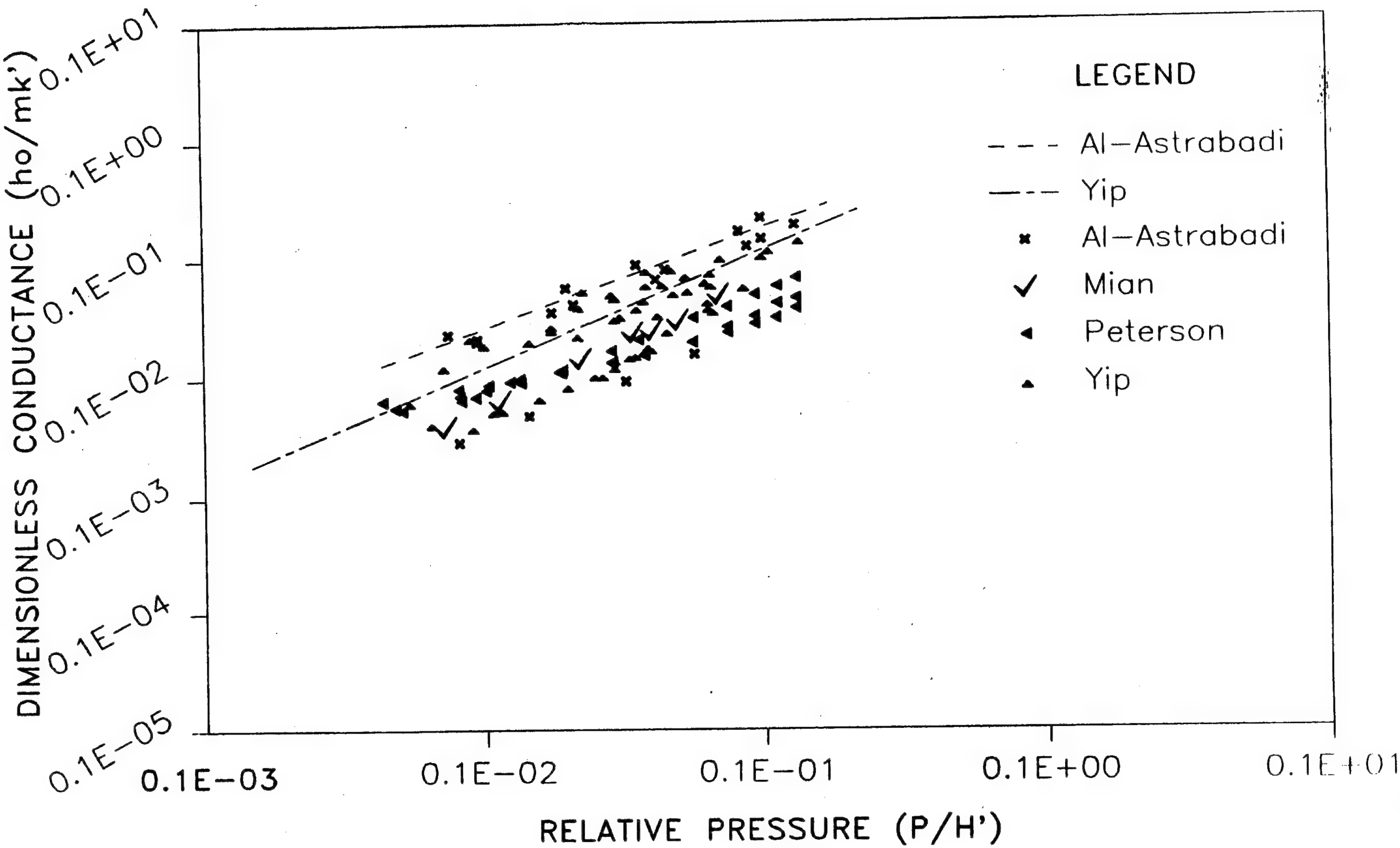
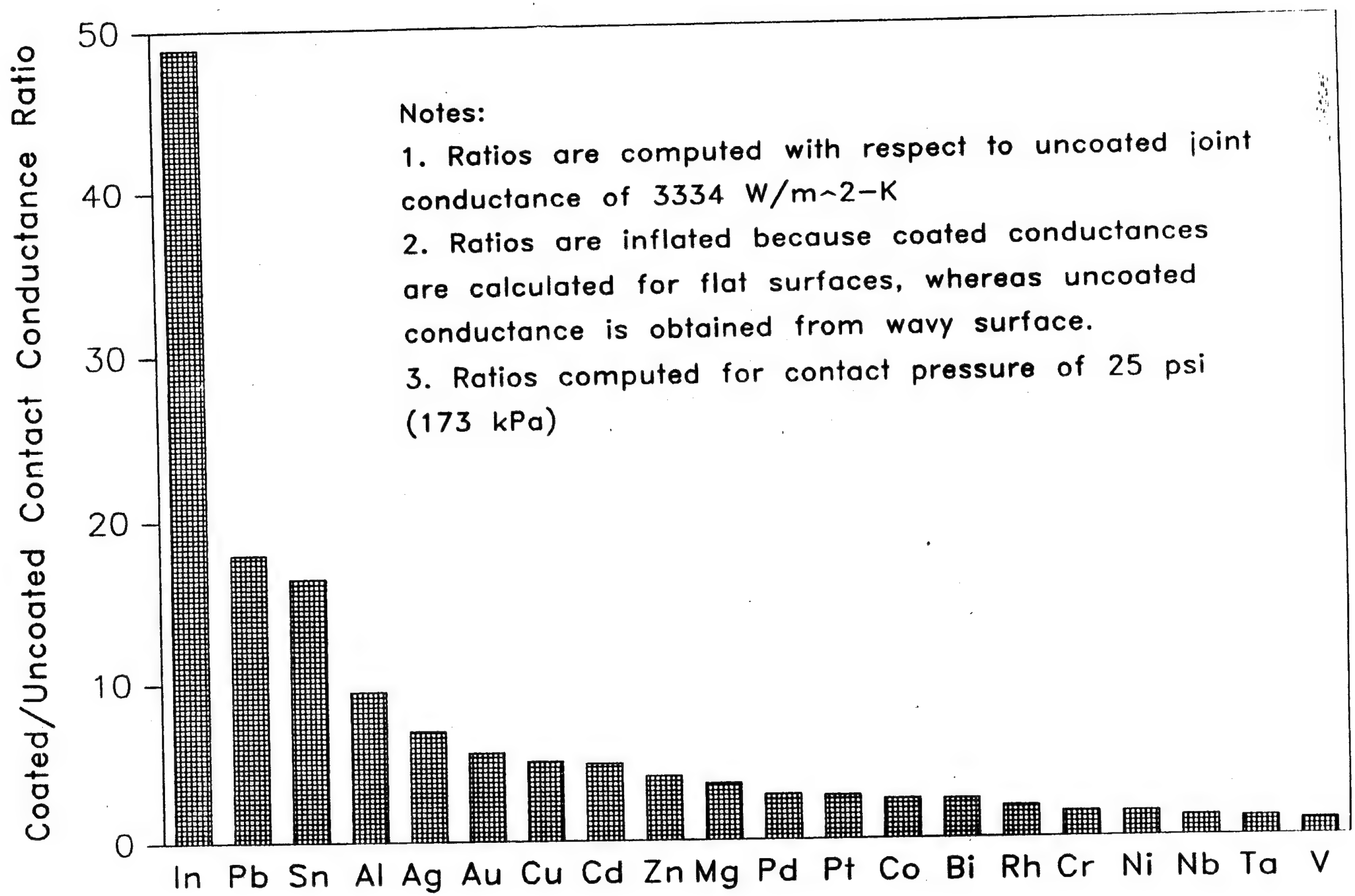


Figure 2: Coated/Uncoated Contact Conductance Ratios for Candidate Coating Metals



APPENDICES

Appendix A

Antonetti and Yovanovich (1985)

$$\frac{h_j' \sigma}{m k'} = 1.25 \left(\frac{P}{H'} \right)^{0.95}$$

O'Callaghan et al. (1981)

$$\frac{1}{R_{t-o}'} = \frac{1}{R_{an}'} + \frac{1}{R_{Mf}}$$

$$= 2\bar{a}_{an} N_{MM} k_{an} + 2\bar{a}_{Mf} N_{Mf} k_{Mf}$$

Peterson and Fletcher (1990)

$$\left(\frac{h_c t}{k_s} \right) \left(\frac{t}{\sigma} \right)^{0.25} = 0.83 \times 10^{-2} \left(\frac{P}{H_s} \right) + 0.11 \times 10^{-4}$$

Al-Astrabadi et al. (1980)

$$\frac{1}{R_{tot}} = \frac{1}{R_{OO}} + \frac{1}{R_{an}}$$

$$= 2\bar{a}_{OO} N_{AOO} k_{OO} + 2\bar{a}_{an} N_{AM} k_{an}$$

Yip (1974)

$$R_{mot} = R_{mo1} + R_{mo2}$$

$$1/R_{mo1} = \frac{\pi}{4\phi_1} \left(k_{m1} a_{m1} N_{m1} + k_{m1} a_{m2} N_{m2} + k_{o1} a_{o1} N_{o1} + k_{o1} a_{o2} N_{o2} \right) + \frac{\pi}{4\phi_2} \left(k_{o1} a_{o1} N_{m1} + k_{o1} a_{o2} N_{m2} \right)$$

$$1/R_{mo2} = \frac{\pi}{4\phi_1} \left(k_{m2} a_{m1} N_{m1} + k_{m2} a_{m2} N_{m2} + k_{o2} a_{o1} N_{o1} + k_{o2} a_{o2} N_{o2} \right) + \frac{\pi}{4\phi_2} \left(k_{o2} a_{o1} N_{m1} + k_{o2} a_{o2} N_{m2} \right)$$

PERIODIC TABLE OF THE ELEMENTS

KEY TO CHART

Atomic Number → 50; Symbol → Sn; Atomic Weight → 118.69; +2 +4 ← Oxidation States; 18 18 4 ← Electron Configuration

1a	2a	3b	4b	5b	6b	7b	8	8	8	1b	2b	3a	4a	5a	6a	7a	0	Orbit
1 H +1 -1 1.0079 1																	2 He 0 4.00260 2	K
3 Li +1 6.94 2-1	4 Be +2 9.01218 2-2											5 B +3 10.81 2-3	6 C +2 +4 -4 12.011 2-4	7 N +1 +2 +3 +4 +5 -1 -2 -3 14.0067 2-5	8 O -2 15.9994 2-6	9 F -1 18.99840 2-7	10 Ne 0 20.17 2-8	K-L
11 Na +1 22.98977 2-8-1	12 Mg +2 24.305 2-8-2	Transition Elements					Group 8			Transition Elements		13 Al +3 26.98154 2-8-3	14 Si +2 +4 -4 28.086 2-8-4	15 P +3 +5 -3 30.97376 2-8-5	16 S +4 +6 -2 32.06 2-8-6	17 Cl +1 +5 +7 -1 35.453 2-8-7	18 Ar 0 39.948 2-8-8	K-L-M
19 K +1 39.09 -8-8-1	20 Ca +2 40.08 -8-8-2	21 Sc +3 44.9559 -8-9-2	22 Ti +2 +3 +4 47.90 -8-10-2	23 V +2 +3 +4 +5 50.941 -8-11-2	24 Cr +2 +3 +6 51.996 -8-13-1	25 Mn +2 +3 +4 +7 54.9380 -8-13-2	26 Fe +2 +3 55.847 -8-14-2	27 Co +2 +3 58.9332 -8-15-2	28 Ni +2 +3 58.71 -8-16-2	29 Cu +1 +2 63.546 -8-18-1	30 Zn +2 65.38 -8-18-2	31 Ga +3 69.72 -8-18-3	32 Ge +2 +4 72.59 -8-18-4	33 As +3 +5 -3 74.9216 -8-18-5	34 Se +4 +6 -2 78.96 -8-18-6	35 Br +1 +5 -1 79.904 -8-18-7	36 Kr 0 83.80 -8-18-8	-L-M-N
37 Rb +1 85.467 -18-8-1	38 Sr +2 87.62 -18-8-2	39 Y +3 88.9059 -18-9-2	40 Zr +4 91.22 -18-10-2	41 Nb +3 +5 92.9064 -18-12-1	42 Mo +6 95.94 -18-13-1	43 Tc +4 +6 +7 98.9062 -18-13-2	44 Ru +3 101.07 -18-15-1	45 Rh +3 102.9055 -18-16-1	46 Pd +2 +4 106.4 -18-18-0	47 Ag +1 107.868 -18-18-1	48 Cd +2 112.40 -18-18-2	49 In +3 114.82 -18-18-3	50 Sn +2 +4 118.69 -18-18-4	51 Sb +3 +5 -3 121.75 -18-18-5	52 Te +4 +6 -2 127.60 -18-18-6	53 I +1 +5 +7 -1 126.9045 -18-18-7	54 Xe 0 131.30 -18-18-8	-M-N-O
55 Cs +1 132.9054 -18-8-1	56 Ba +2 137.34 -18-8-2	57* La +3 138.9055 -18-9-2	72 Hf +4 178.49 -32-10-2	73 Ta +5 180.947 -32-11-2	74 W +6 183.85 -32-12-2	75 Re +4 +6 +7 186.2 -32-13-2	76 Os +3 +4 190.2 -32-14-2	77 Ir +3 +4 192.22 -32-15-2	78 Pt +2 +4 195.09 -32-16-2	79 Au +1 +3 196.9665 -32-18-1	80 Hg +1 +2 200.59 -32-18-2	81 Tl +1 +3 204.37 -32-18-3	82 Pb +2 +4 207.2 -32-18-4	83 Bi +3 +5 208.9806 -32-18-5	84 Po +2 +4 (209) -32-18-6	85 At (210) -32-18-7	86 Rn 0 (222) -32-18-8	-N-O-P
87 Fr +1 (223) -18-8-1	88 Ra +2 226.0254 -18-8-2	89** Ac +3 (227) -18-9-2	104 — -32-10-2	105 —														O-P-Q

*Lanthanides	58 Ce +3 +4 140.12 -20-8-2	59 Pr +3 140.9077 -21-8-2	60 Nd +3 144.24 -22-8-2	61 Pm +3 (145) -23-8-2	62 Sm +2 +3 150.4 -24-8-2	63 Eu +2 +3 151.96 -25-8-2	64 Gd +3 157.25 -25-9-2	65 Tb +3 158.9254 -27-8-2	66 Dy +3 162.50 -28-8-2	67 Ho +3 164.9304 -29-8-2	68 Er +3 167.26 -30-8-2	69 Tm +3 168.9342 -31-8-2	70 Yb +2 +3 173.04 -32-8-2	71 Lu +3 174.97 -32-9-2		N O P
**Actinides	90 Th +4 232.0381 -18-10-2	91 Pa +5 +4 231.0359 -20-9-2	92 U +3 +4 +5 +6 238.029 -21-9-2	93 Np +3 +4 +5 +6 237.0482 -22-9-2	94 Pu +3 +4 +5 +6 (244) -24-8-2	95 Am +3 +4 +5 +6 (243) -25-8-2	96 Cm +3 (247) -25-9-2	97 Bk +3 +4 (247) -27-8-2	98 Cf +3 (251) -28-8-2	99 Es (254) -29-8-2	100 Fm (257) -30-8-2	101 Md (256) -31-8-2	102 No (254) -32-8-2	103 Lr -32-9-2	104 (257)	O P Q

Numbers in parentheses are mass numbers of most stable isotope of that element

Source: Weats, R.C., Ed., 1974, *CRC Handbook of Chemistry and Physics*, 55th Edition, Chemical Rubber Company.

Appendix C

Published Experimental Data on Coated Contacts

Key to tabular quantities:

Bc	Linear thermal expansion coefficient of coating, μm/mK
Del-1,2	Roughness of surfaces 1 and 2 (RMS/Avg.), μm
Ec	Elastic (Young's) modulus of coating, GPa
Es	Elastic (Young's) modulus of substrate, GPa
h	Thermal contact conductance, W/m^2K
Hc	Hardness of coating, MPa
Hs	Hardness of substrate, MPa
Hc, BHN	Brinell Hardness of coating, kg/mm^2
Hs, BHN	Brinell Hardness of substrate, kg/mm^2
kc	Thermal conductivity of coating, W/mK
ks	Thermal conductivity of substrate, W/mK
P	Apparent contact pressure, kPa
Slope-1,2	Asperity slope of surfaces 1 an 2 (Absolute/Radians)
Tm	Mean interface temperature, C
t1,2	Coating thickness on surfaces 1 and 2, μm
wave-1,2	Waviness (flatness deviation) of surfaces 1 and 2 (Avg./Max.), μm

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
1	Fried and	Substrate	367	210	29.3	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5	-----	-----
	Kelley,	SS 304	987	615	29.3	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
	1965		1646	1201	29.4	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
		Vapor	2502	1636	30.3	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
		Deposited	5816	3209	31.3	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
		Al	7978	4113	31.5	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
			3863	1477	30.5	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
			3018	1476	30.5	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
			296	177	29.7	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
			599	255	30.6	1.5	1.9	260	70	2550.6	686.7	15.2	237	25	207	68	0.6	1	1.3	2.5		
		Mg	441	337	31.9	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			1000	473	29.6	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			1646	741	30.4	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			448	96	34.8	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			607	94	34.3	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			1489	729	35.8	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			2151	2173	33.6	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			5640	13110	35.4	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			7267	20409	35.4	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			3806	6965	34.5	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			2765	2885	35.4	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
			648	172	34.8	2	0	260	70	2550.6	686.7	15.2	156	25	207	40	0.6	0.3	0	1.3		
2	Malkov and	Substrate	450	3170	250-	25	0	163	300	1599.03	2943	18.2	66	13	207	207	1.7	1.7	12	12	-----	-----
	Dobashin,	SS-	1150	3770	550	25	0	163	300	1599.03	2943	18.2	66	13	207	207	1.7	1.7	12	12		
	1969	Kh18N9T	2650	4760		25	0	163	300	1599.03	2943	18.2	66	13	207	207	1.7	1.7	12	12		
		Platings	4150	5260		25	0	163	300	1599.03	2943	18.2	66	13	207	207	1.7	1.7	12	12		
		Ni	5600	5560		25	0	163	300	1599.03	2943	18.2	66	13	207	207	1.7	1.7	12	12		
		Ag	450	3330		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.85	1.85	40	40		
			1150	4260		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.85	1.85	40	40		
			2650	5560		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.85	1.85	40	40		
			4150	7140		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.85	1.85	40	40		
			5600	9520		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.85	1.85	40	40		
			450	8000		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.075	1.075	11	11		
			1150	9520		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.075	1.075	11	11		
			2650	11760		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.075	1.075	11	11		
			4150	12500		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.075	1.075	11	11		
			5600	13330		25	0	163	100	1599.03	981	18.2	405	19	207	71	1.075	1.075	11	11		
		Cu	450	10000		25	0	163	140	1599.03	1373.4	18.2	370	16.6	207	125	0.925	0.925	12	12		
			1150	16670		25	0	163	140	1599.03	1373.4	18.2	370	16.6	207	125	0.925	0.925	12	12		
			2650	50000		25	0	163	140	1599.03	1373.4	18.2	370	16.6	207	125	0.925	0.925	12	12		
			4150	100000		25	0	163	140	1599.03	1373.4	18.2	370	16.6	207	125	0.925	0.925	12	12		
			5600	100000		25	0	163	140	1599.03	1373.4	18.2	370	16.6	207	125	0.925	0.925	12	12		

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
3	O'Callaghan	Substrate	4000	4080	47-	2.8	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	5.16	1	1	0.0157	0.1045
	et al.,	SS EN58B	9980	10180	53	2.8	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	5.16	1	1	0.0157	0.1045
	1981		15670	19420		2.8	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	5.16	1	1	0.0157	0.1045
		Coating	21890	25450		2.8	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	5.16	1	1	0.0157	0.1045
		Sn 46-59	15670	81300		12	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	5.82	1	1	0.0157	0.1068
		1 Surface	21890	58140		12	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	5.82	1	1	0.0157	0.1068
			4000	27780		28	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.341	1	1	0.0157	0.1127
			9980	33900		28	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.341	1	1	0.0157	0.1127
			15670	51020		28	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.341	1	1	0.0157	0.1127
			21890	101800		28	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.341	1	1	0.0157	0.1127
			4000	14040		106	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.548	1	1	0.0157	0.1164
			9980	18520		106	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.548	1	1	0.0157	0.1164
			15670	45250		106	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.548	1	1	0.0157	0.1164
			21890	81300		106	0	204	10.5	2001.24	103.005	15	60.2	20	207	44	0.3	6.548	1	1	0.0157	0.1164
4	Antonetti &	Substrate	650	12800	85-	1.2	0	360	40	3531.6	392.4	77	425	19	207	71	0.17	1.24	1	1	0.025	0.129
	Yovanovich,	Ni 200	1100	22500	206	1.2	0	360	40	3531.6	392.4	77	425	19	207	71	0.17	1.24	1	1	0.025	0.129
	1985		1630	32500		1.2	0	360	40	3531.6	392.4	77	425	19	207	71	0.17	1.24	1	1	0.025	0.129
		Vapor	2000	42000		1.2	0	360	40	3531.6	392.4	77	425	19	207	71	0.17	1.24	1	1	0.025	0.129
		deposited	2650	52000		1.2	0	360	40	3531.6	392.4	77	425	19	207	71	0.17	1.24	1	1	0.025	0.129
		Ag	3100	58000		1.2	0	360	40	3531.6	392.4	77	425	19	207	71	0.17	1.24	1	1	0.025	0.129
			520	22000		6.3	0	360	40	3531.6	392.4	77	425	19	207	71	0.14	1.3	1	1	0.018	0.14
		Series B	920	39000		6.3	0	360	40	3531.6	392.4	77	425	19	207	71	0.14	1.3	1	1	0.018	0.14
		del rms	1300	49000		6.3	0	360	40	3531.6	392.4	77	425	19	207	71	0.14	1.3	1	1	0.018	0.14
		avg=1.28	1820	68000		6.3	0	360	40	3531.6	392.4	77	425	19	207	71	0.14	1.3	1	1	0.018	0.14
			600	2350		2.4	0	280	40	2746.8	392.4	77	425	19	207	71	0.14	8.62	1	1	0.018	0.35
			980	3650		2.4	0	280	40	2746.8	392.4	77	425	19	207	71	0.14	8.62	1	1	0.018	0.35
			1500	5700		2.4	0	280	40	2746.8	392.4	77	425	19	207	71	0.14	8.62	1	1	0.018	0.35
			1960	7600		2.4	0	280	40	2746.8	392.4	77	425	19	207	71	0.14	8.62	1	1	0.018	0.35
		Series C	2730	9600		2.4	0	280	40	2746.8	392.4	77	425	19	207	71	0.14	8.62	1	1	0.018	0.35
		del rms	3600	13700		2.4	0	280	40	2746.8	392.4	77	425	19	207	71	0.14	8.62	1	1	0.018	0.35
		avg=8.32	580	5400		7.2	0	280	40	2746.8	392.4	77	425	19	207	71	0.17	8.31	1	1	0.025	0.338
			1000	10500		7.2	0	280	40	2746.8	392.4	77	425	19	207	71	0.17	8.31	1	1	0.025	0.338
			1520	14600		7.2	0	280	40	2746.8	392.4	77	425	19	207	71	0.17	8.31	1	1	0.025	0.338
			2050	18500		7.2	0	280	40	2746.8	392.4	77	425	19	207	71	0.17	8.31	1	1	0.025	0.338
			2700	24500		7.2	0	280	40	2746.8	392.4	77	425	19	207	71	0.17	8.31	1	1	0.025	0.338
			3700	33800		7.2	0	280	40	2746.8	392.4	77	425	19	207	71	0.17	8.31	1	1	0.025	0.338
			590	9500		18	0	280	40	2746.8	392.4	77	425	19	207	71	0.19	8.03	1	1	0.024	0.348
			1120	17500		18	0	280	40	2746.8	392.4	77	425	19	207	71	0.19	8.03	1	1	0.024	0.348
			1500	22800		18	0	280	40	2746.8	392.4	77	425	19	207	71	0.19	8.03	1	1	0.024	0.348
			2040	32000		18	0	280	40	2746.8	392.4	77	425	19	207	71	0.19	8.03	1	1	0.024	0.348
			2700	44000		18	0	280	40	2746.8	392.4	77	425	19	207	71	0.19	8.03	1	1	0.024	0.348
			3700	58000		18	0	280	40	2746.8	392.4	77	425	19	207	71	0.19	8.03	1	1	0.024	0.348

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
4	Antonetti &	Substrate	560	3850	85-	1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
	Yovanovich,	Ni 200	1030	6200	206	1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
	1985		1490	9800		1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
		Vapor	1940	13200		1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
	Cont.	deposited	2500	16700		1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
		Ag	3050	20000		1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
			3550	23500		1.4	0	300	40	2943	392.4	77	425	19	207	71	0.19	4.06	1	1	0.03	0.231
			560	7200		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
		Series A	980	12500		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
		del rms	1520	19000		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
		avg=4.27	2000	25500		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
			2450	31000		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
			3050	38000		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
			3600	48000		5.1	0	300	40	2943	392.4	77	425	19	207	71	0.2	4.24	1	1	0.031	0.233
			540	12000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			980	22000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			1500	35000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			1980	48000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			2520	51000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			3000	61000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			3600	95000		39.5	0	300	40	2943	392.4	77	425	19	207	71	0.27	4.45	1	1	0.038	0.252
			600	2350		0.81	0	300	40	2943	392.4	77	425	19	207	71	0.14	4.38	1	1	0.022	0.232
			1000	3550		0.81	0	300	40	2943	392.4	77	425	19	207	71	0.14	4.38	1	1	0.022	0.232
			1600	5200		0.81	0	300	40	2943	392.4	77	425	19	207	71	0.14	4.38	1	1	0.022	0.232
			2050	7000		0.81	0	300	40	2943	392.4	77	425	19	207	71	0.14	4.38	1	1	0.022	0.232
			2750	8300		0.81	0	300	40	2943	392.4	77	425	19	207	71	0.14	4.38	1	1	0.022	0.232
			3700	12800		0.81	0	300	40	2943	392.4	77	425	19	207	71	0.14	4.38	1	1	0.022	0.232
			600	3200		1.2	0	300	40	2943	392.4	77	425	19	207	71	0.21	4.19	1	1	0.027	0.224
			1070	5700		1.2	0	300	40	2943	392.4	77	425	19	207	71	0.21	4.19	1	1	0.027	0.224
			1500	8300		1.2	0	300	40	2943	392.4	77	425	19	207	71	0.21	4.19	1	1	0.027	0.224
			2100	11000		1.2	0	300	40	2943	392.4	77	425	19	207	71	0.21	4.19	1	1	0.027	0.224
			2700	13600		1.2	0	300	40	2943	392.4	77	425	19	207	71	0.21	4.19	1	1	0.027	0.224
			3500	19500		1.2	0	300	40	2943	392.4	77	425	19	207	71	0.21	4.19	1	1	0.027	0.224

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
5	Kang, 1989	Substrate	79.5	1006	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
		Al 6061-T6	176.6	2212	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			264.9	3232	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
		Vapor	353.2	4278	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
		deposited	446	5302	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
		Sn	529.9	6294	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			622.6	7198	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			706.5	7889	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			794.8	8388	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			891.9	9126	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			1055.3	10138	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			1227.5	10909	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			1413	12028	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			1589.6	12803	25	0.2505	0	100	5	981	49.05	179	65.76	20	69	44	0.856	0.6985	2.54	2.489	0.077	0.084
			101.6	712	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			181	1058	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			269.4	1648	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			348.8	2006	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			441.6	2659	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			534.3	3113	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			613.8	3691	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			710.9	4226	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			799.2	4708	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			883.1	5239	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			1059.7	6039	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			1236.4	7018	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			1404.2	7686	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085
			1594	8318	25	0.7575	0	100	5	981	49.05	179	65.76	20	69	44	0.6909	0.6858	2.235	2.337	0.089	0.085

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
5	Kang, 1989	Substrate	97.1	921	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
		Al 6061-T6	181	1200	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
	Cont.		264.9	1729	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
		Vapor	353.2	2243	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
		deposited	446	2731	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
		Sn	529.9	3152	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			653.5	3825	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			710.9	4114	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			803.6	4499	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			878.7	4923	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			1108.3	5889	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			1231.9	6424	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			1404.2	7158	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			1589.6	7826	25	1.2598	0	100	5	981	49.05	179	65.76	20	69	44	0.6858	0.7417	2.286	2.489	0.08	0.079
			75.1	172	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			172.2	291	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			264.9	444	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			348.8	540	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			454.8	710	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			525.5	818	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			609.3	928	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			706.5	1042	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			794.8	1133	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			874.3	1264	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			1059.7	1467	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			1231.9	1689	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			1404.2	1925	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078
			1594	2140	25	1.8202	0	100	5	981	49.05	179	65.76	20	69	44	0.7417	0.7747	2.54	2.591	0.08	0.078

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
5	Kang, 1989	Substrate	88.3	4818	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
		Al 6061-T6	172.2	8626	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
	Cont.		278.2	11625	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
		Vapor	348.8	14584	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
		deposited	441.6	16485	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
		In	529.9	18225	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			609.3	19601	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			710.9	21181	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			794.8	22045	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			887.5	23509	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			1055.3	26125	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			1236.4	28109	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			1413	30982	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			1580.8	33371	25	2.5003	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6401	0.6858	2.235	2.337	0.083	0.085
			106	1920	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			176.6	2530	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			264.9	3725	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			353.2	4833	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			450.4	7098	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			534.3	8458	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			613.8	9589	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			706.5	11396	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			808.1	12091	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			905.2	14134	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			1059.7	16381	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			1231.9	18180	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			1421.8	20203	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081
			1589.6	21611	25	0.2762	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.6477	2.286	2.235	0.084	0.081

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Ha, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
5	Kang, 1989	Substrate	92.7	3433	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
		Al 6061-T6	264.9	4896	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
	Cont.		353.2	5356	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
		Vapor	441.6	5793	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
		deposited	534.3	6277	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
		In	613.8	6704	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			710.9	7304	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			794.8	7630	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			874.3	8198	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			1059.7	9043	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			1231.9	10940	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			1448.3	12439	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			1585.2	13591	25	3.7053	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6553	0.7747	2.489	2.54	0.084	0.085
			75.1	3703	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			203.1	5175	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			260.5	6430	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			353.2	7743	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			441.6	9307	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			534.3	11181	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			622.6	13266	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			702.1	14993	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			803.6	16399	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			878.7	18502	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			1068.6	19822	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			1231.9	21589	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			1404.2	24151	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088
			1589.6	26265	25	1.4417	0	100	1	981	9.81	179	23.88	32.1	69	12.74	0.6985	0.7112	2.032	2.337	0.082	0.088

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
5	Kang, 1989	Substrate	101.6	1995	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
		Al 6061-T6	181	3005	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
	Cont.		278.2	4053	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
		Vapor	476.9	5983	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
		deposited	538.7	6730	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
		Pb	622.6	7484	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			710.9	8299	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			781.6	8955	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			891.9	9534	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			1059.7	10469	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			1231.9	11061	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			1408.6	11964	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			1589.6	12199	25	0.2518	0	100	4	981	39.24	179	37.04	29	69	19	0.7112	0.6782	2.413	2.413	0.078	0.08
			106	3667	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			176.6	5549	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			273.8	7606	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			357.7	8896	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			441.6	10328	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			543.1	11922	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			622.6	12611	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			706.5	13538	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			799.2	15020	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			883.1	15937	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			1064.2	17915	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			1289.3	20134	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			1413	21258	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083
			1585.2	22457	25	1.7784	0	100	4	981	39.24	179	37.04	29	69	19	0.6782	0.7874	2.337	2.667	0.081	0.083

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
5	Kang, 1989	Substrate	110.4	3353	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
		Al 6061-T6	181	4069	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
	Cont.		269.4	5045	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
		Vapor	344.4	5904	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
		deposited	446	6539	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
		Pb	534.3	7247	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			622.6	7650	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			706.5	8631	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			794.8	9332	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			900.8	10598	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			1055.3	11749	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			1236.4	13059	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			1413	14520	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			1576.4	15916	25	4.0052	0	100	4	981	39.24	179	37.04	29	69	19	0.8052	0.7163	2.54	2.337	0.078	0.081
			110.4	2534	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			176.6	3371	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			264.9	4738	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			357.7	5633	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			446	6889	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			534.3	7187	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			613.8	8384	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			710.9	9205	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			794.8	9838	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			878.7	10606	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			1059.7	11838	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			1236.4	12675	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			1404.2	13675	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085
			1589.6	14570	25	5.0222	0	100	4	981	39.24	179	37.04	29	69	19	0.6909	0.6985	2.337	2.235	0.085	0.085

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
6	Chung et al.	Substrate	87.8	1650	-----	25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6	-----	-----	-----	-----
	1990	Al 6061-T6	180.9	1780		25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
	Metal coat		274.1	1790		25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		Vapor	522.9	1990		25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		deposited	280	1900		25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		Al	168.2	1850		25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		1 surface	104.5	1770		25.4	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			110	920		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			175.8	930		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			284.6	1040		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			524.6	1360		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			276.6	1110		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			176	1050		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			95.8	940		50.8	0	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			112.4	1160		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			183.5	1130		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			275.8	1220		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			511	1400		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			282.7	1410		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			168.3	1420		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			96.5	1330		25.4	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			103.5	1460		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			171.1	1560		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			274.4	1570		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			516.2	1870		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			276.5	1900		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			169.5	1690		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			93.3	1680		50.8	0	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
6	Chung et al.	Substrate	110.6	2650	-----	12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6	-----	-----	-----	-----
	1990	Al 6061-T6	173.8	2700		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
	Metal coat		275.7	2890		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		Vapor	517.9	3630		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		deposited	279.2	3430		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		Al	171.2	3200		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
		2 Surface	105.4	2930		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			103.1	3070		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			170.3	2600		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			275.7	2620		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			513.5	2960		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			280.9	2880		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			167.7	2840		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			102.7	2930		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	1.6	1.6				
			100.9	3010		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			167.7	3020		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			277.4	3620		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			515.7	4400		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			279.9	3890		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			175.5	3520		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			114.1	3370		12.7	12.7	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			96.5	2490		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			171.2	2740		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			280.9	2790		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			517.1	3380		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			279.2	3210		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			170.3	2810		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				
			114.1	3220		25.4	25.4	95	20	931.95	196.2	167	237	25	69	62	3.2	3.2				

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
6	Chung et al.	Substrate	108.9	2070	-----	25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6	-----	-----	-----	-----
	1990	Al 6061-T6	175.5	1980		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
	Metal coat		275.7	2100		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		Vapor	519.7	2270		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		deposited	280	2320		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		Pb	166.8	2430		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		1 surface	103.6	2290		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			104.4	1810		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			172	2010		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			277.4	2110		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			522.3	2180		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			273.9	2040		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			186.2	2390		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			104.5	2280		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			114.1	2160		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			175.5	2230		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			275.7	2450		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			517.9	2750		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			282.7	2380		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			166.3	2600		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			102.7	2470		25.4	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			100.9	1970		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			176.4	1980		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			280.9	2180		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			517.1	2130		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			277.4	2320		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			171.7	2250		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			97.4	2420		50.8	0	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
6	Chung et al.	Substrate	122.9	2050	-----	12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6	-----	-----	-----	-----
	1990	Al 6061-T6	170.3	2120		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
	Metal coat		287.9	2480		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		Vapor	517.1	2720		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		deposited	274.8	2380		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		Pb	167.7	2050		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
		2 surface	105.4	1880		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			104.5	2180		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			175.5	2190		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			286.2	2300		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			519.7	2580		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			254.6	2590		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			184.4	2790		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			88.7	3550		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	1.6	1.6				
			105.4	2160		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			166.8	2250		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			273.9	2260		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			517.9	2940		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			280.9	2660		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			169.4	2280		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			105.4	2670		12.7	12.7	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			105.4	1770		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			174.7	1790		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			277.4	1830		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			536.4	2550		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			289.7	2560		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			177.3	2720		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				
			107.1	2800		25.4	25.4	95	4	931.95	39.24	167	35.3	29	69	19	3.2	3.2				

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
6	Chung et al.	Substrate	105.2	2150	-----	25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6	-----	-----	-----	-----
	1990	Al 6061-T6	176.5	2120		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
	Metal coat		275.8	2150		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		Vapor	518	2260		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		deposited	280.9	2310		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		In	163.3	2320		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		1 surface	100.9	2860		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			112.3	1770		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			175.5	1720		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			277.4	1730		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			510.9	2050		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			277.4	1930		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			166.8	2070		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			83.4	2100		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			100.9	2960		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			175.5	3000		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			275.7	3050		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			509.2	3370		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			280.9	3460		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			166.8	3630		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			105.4	3370		25.4	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			107.9	4000		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			168.6	4090		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			272.9	4530		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			522.4	5530		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			280.1	5430		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			175.5	5210		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			98.3	5580		50.8	0	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
6	Chung et al.	Substrate	114.1	3680	-----	12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6	-----	-----	-----	-----
	1990	Al 6061-T6	168.5	3350		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
	Metal coat		275.7	3800		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		Vapor	507.4	4310		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		deposited	270.4	3990		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		In	171.2	4180		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
		2 surface	110.6	4390		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			105.4	4160		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			175.5	6100		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			278.3	5150		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			522.4	6300		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			275.7	6060		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			168.7	5680		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	1.6	1.6				
			105.4	4980		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			140.5	3200		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			173.8	3880		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			272.1	3970		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			517.1	3840		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			307.2	4190		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			157.1	4200		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			104.5	4540		12.7	12.7	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			115	5300		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			180.9	6630		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			276.6	6770		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			526.7	6680		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			254.6	9060		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			192.2	6620		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				
			106.2	5970		25.4	25.4	95	1	931.95	9.81	167	23.9	32.1	69	12.74	3.2	3.2				

Metallic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
7	Chung et al.	Substrate	114.1	1460	60	0.19	0.19	-----	193.578	-----	1899	140.5	398	16.6	69	125	0.17	0.23	-----	-----	-----	-----
	1991	Al	245.8	1580	60	0.19	0.19		192.457		1888	140.5	398	16.6	69	125	0.17	0.23				
		6061-T651	374.9	1900	60	0.19	0.19		191.845		1882	140.5	398	16.6	69	125	0.17	0.23				
	Transitional		456.5	2060	60	0.19	0.19		191.539		1879	140.5	398	16.6	69	125	0.17	0.23				
	Buffering	Vapor	114.1	3040	60	0.19	0.19		187.258		1837	140.5	398	16.6	69	125	0.29	0.32				
	Interface,	deposited	249.3	3460	60	0.19	0.19		186.137		1826	140.5	398	16.6	69	125	0.29	0.32				
	(TBI)	Pure Cu	377.5	3680	60	0.19	0.19		185.525		1820	140.5	398	16.6	69	125	0.29	0.32				
			482.8	4210	60	0.19	0.19		185.219		1817	140.5	398	16.6	69	125	0.29	0.32				
			196.6	2320	60	0.24	0.24		155.046		1521	140.5	398	16.6	69	125	3.2	2.8				
			298.5	2560	60	0.24	0.24		154.638		1517	140.5	398	16.6	69	125	3.2	2.8				
			338	2800	60	0.24	0.24		154.434		1515	140.5	398	16.6	69	125	3.2	2.8				
			412.6	2970	60	0.24	0.24		154.23		1513	140.5	398	16.6	69	125	3.2	2.8				
			131.7	2390	60	0.24	0.24		153.517		1506	140.5	398	16.6	69	125	3.8	3.3				
			248.4	3080	60	0.24	0.24		152.701		1498	140.5	398	16.6	69	125	3.8	3.3				
			377.5	3110	60	0.24	0.24		152.192		1493	140.5	398	16.6	69	125	3.8	3.3				
			477.7	3660	60	0.24	0.24		151.988		1491	140.5	398	16.6	69	125	3.8	3.3				
		Vapor	121.5	1760	60	0.25	0.25		203.262		1994	140.5	-----	-----	69	-----	0.15	0.17				
		deposited	237	1880	60	0.25	0.25		202.141		1983	140.5			69		0.15	0.17				
		Cu/C	377.5	2180	60	0.25	0.25		201.325		1975	140.5			69		0.15	0.17				
			482.8	2500	60	0.25	0.25		200.917		1971	140.5			69		0.15	0.17				
			114.1	2600	60	0.45	0.45		194.088		1904	140.5			69		0.26	0.29				
			237	2840	60	0.45	0.45		192.864		1892	140.5			69		0.26	0.29				
			377.5	3190	60	0.45	0.45		192.151		1885	140.5			69		0.26	0.29				
			456.5	3630	60	0.45	0.45		191.845		1882	140.5			69		0.26	0.29				
			149.2	1620	60	0.45	0.45		164.628		1615	140.5			69		1.91	1.66				
			250.2	1740	60	0.45	0.45		163.914		1608	140.5			69		1.91	1.66				
			368.7	2220	60	0.45	0.45		163.303		1602	140.5			69		1.91	1.66				
			500.4	2710	60	0.45	0.45		162.895		1598	140.5			69		1.91	1.66				
			127.3	2030	60	0.25	0.25		155.352		1524	140.5			69		3.4	3.7				
			263.4	2170	60	0.25	0.25		154.332		1514	140.5			69		3.4	3.7				
			377.5	2510	60	0.25	0.25		153.925		1510	140.5			69		3.4	3.7				
			500.4	2810	60	0.25	0.25		153.517		1506	140.5			69		3.4	3.7				

Oxide and Anodic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
1	Yip, 1974	Substrate	1263	2475.25	-----	0.075	0.075	110	-----	1079.1	-----	167	1.03	-----	68	-----	1.531	1.531	0	0	0.136	0.136
		Al 6061-T6	1403	2283.11		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			2104	3154.57		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
		Oxide coat	2266	3225.81		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
		Series A	3075	4065.04		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			3885	5025.13		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			4956	6172.84		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			5180	6172.84		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			5719	7246.38		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			5719	8264.46		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			6475	8849.56		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			6798	9090.91		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			7554	10787.5		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			7770	10235.4		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			8201	19762.8		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			8849	14471.8		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			1241	25380.7		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			1252	22471.9		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			1295	21186.4		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
			1673	33670		0.075	0.075	110		1079.1		167	1.03		68		1.531	1.531	0	0	0.136	0.136
		Series B	1209	7462.69		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			1360	6535.95		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			2374	9345.79		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			2374	8695.65		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			2968	13404.8		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			3075	18248.2		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			3885	17241.4		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			3237	16025.6		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			5180	20366.6		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			5180	27027		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			5935	20661.2		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			9064	34129.7		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			3939	11210.8		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311
			6043	27548.2		0.075	0.075	110		1079.1		167	1.03		68		6.619	6.619	0	0	0.311	0.311

Oxide and Anodic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
1	Yip, 1974	Substrate	690.6	2314.81		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
		Al 6061-T6	917.2	4545.45		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
	Cont.		1888	7462.69		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
		Oxide coat	2784	8130.08		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
		Series C	3777	11337.9		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			4532	13831.3		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			4802	16207.5		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			6151	18450.2		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			6798	25773.2		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			6906	19230.8		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			7985	22935.8		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			8309	27322.4		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			12730	37735.8		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			13380	42016.8		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			17270	50505.1		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
			8741	21413.3		0.075	0.075	110		1079.1		167	1.03		68		6.619	1.531	0	0	0.311	0.136
2	Mian et al.,	Substrate	2550	2439.02	----	0	0.35	170	358	1667.7	3511.98	47	0.875	----	207	----	0.08	0.08	0	0	0.028	0.028
	1979	Mild Steel,	4000	3921.57		0	0.35	170	358	1667.7	3511.98	47	0.875		207		0.08	0.08	0	0	0.028	0.028
		EN3B	7800	8695.65		0	0.35	170	358	1667.7	3511.98	47	0.875		207		0.08	0.08	0	0	0.028	0.028
			12000	14285.7		0	0.35	170	358	1667.7	3511.98	47	0.875		207		0.08	0.08	0	0	0.028	0.028
		Oxide coat	14000	14705.9		0	0.35	170	358	1667.7	3511.98	47	0.875		207		0.08	0.08	0	0	0.028	0.028
			17500	17543.9		0	0.35	170	358	1667.7	3511.98	47	0.875		207		0.08	0.08	0	0	0.028	0.028
			24500	28571.4		0	0.35	170	358	1667.7	3511.98	47	0.875		207		0.08	0.08	0	0	0.028	0.028
3	Al-Astrabadi	Substrate	2000	3571.43	----	0.118	0.118	170	358	1667.7	3511.98	47	0.875	----	207	----	1.57	1.67	0	0	0.132	0.135
	et al.,	Mild Steel,	5100	8547.01		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.132	0.135
	1980	EN3B	9000	13513.5		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.132	0.135
			20500	25641		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.132	0.135
		Oxide coat	24500	33333.3		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.13	0.134
			2000	5263.16		0.0546	0.0546	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.13	0.134
			3700	8928.57		0.0546	0.0546	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.13	0.134
			8600	16666.7		0.0546	0.0546	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.13	0.134
			20500	35087.7		0.0546	0.0546	170	358	1667.7	3511.98	47	0.875		207		1.57	1.67	0	0	0.18	0.19
			2350	3636.36		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.98	2.03	0	0	0.18	0.19
			5100	6896.55		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.98	2.03	0	0	0.18	0.19
			10600	13698.6		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.98	2.03	0	0	0.18	0.19
			20500	21276.6		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.98	2.03	0	0	0.18	0.19
			30000	32258.1		0.118	0.118	170	358	1667.7	3511.98	47	0.875		207		1.98	2.03	0	0	0.038	0.04
			2850	3333.33		0.1	0.1	170	358	1667.7	3511.98	47	0.875		207		0.12	0.123	0	0	0.038	0.04
			5100	5555.56		0.1	0.1	170	358	1667.7	3511.98	47	0.875		207		0.12	0.123	0	0	0.038	0.04
			11300	10638.3		0.1	0.1	170	358	1667.7	3511.98	47	0.875		207		0.12	0.123	0	0	0.038	0.04
			20000	17857.1		0.1	0.1	170	358	1667.7	3511.98	47	0.875		207		0.12	0.123	0	0		

Oxide and Anodic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
4	Peterson &	Substrate	447.7	58.76	25	61	0	95	-----	931.95	-----	179	1.03	-----	68	-----	3.607	4.877	0.884	1.016	0.224	0.192
	Fletcher,	Al 6061-T6	763.5	73.43	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
	1990		948.1	81.89	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
		Anodized	1264.1	94.34	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
		Coating	1729.4	115.8	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			2677.5	172.4	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			3344.7	214.1	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			5267.2	324.9	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			6970.3	398.4	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			8769.9	503.4	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			10508	591.3	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			12281	692.8	25	61	0	95		931.95		179	1.03		68		3.607	4.877	0.884	1.016	0.224	0.192
			333.6	53.71	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			737.4	72.4	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			939.3	82.95	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			1229.3	95.72	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			1694.3	192.1	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			3037.4	235.1	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			3458.8	245.4	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			5197	315.1	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			6952.7	391.6	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			8717.3	477.9	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			10429	559.3	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			12238	644.5	25	78.74	0	95		931.95		179	1.03		68		3.099	4.877	1.334	1.016	0.205	0.192
			640.9	78.96	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			965.7	94.6	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			1430.9	122.7	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			1597.7	129.4	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			2563.4	174.5	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			3564.2	216.6	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			5302.3	289.6	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			7040.5	375.8	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			9913.8	454.3	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			10473	538.7	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			12281	611.6	25	85.6	0	95		931.95		179	1.03		68		5.334	4.877	0.889	1.016	0.248	0.192
			474.1	54.58	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
			772.5	65.79	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
			869.1	69.95	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
			1158.8	93.26	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
			1773.3	110.3	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
			2668.7	134.4	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192

Oxide and Anodic Coatings

No.	Reference	Materials	Press, P kPa	Cond, h W/m2K	Tm C	t1 um	t2 um	Hs, BHN kg/mm2	Hc, BHN kg/mm2	Hs MPa	Hc MPa	ks W/mK	kc W/mK	Bc um/mK	Es GPa	Ec GPa	Del-1 um	Del-2 um	Wave-1 um	Wave-2 um	Slope-1	Slope-2
4	Peterson &	Substrate	3502.7	154	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
	Fletcher,	Al 6061-T6	6987.9	263.4	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
	1990		8752.4	323.6	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
		Anodized	10526	413.7	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
	Cont.	Coating	12290	455.8	25	118.1	0	95		931.95		179	1.03		68		3.683	4.877	0.762	1.016	0.242	0.192
			289.7	47.45	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			711.1	66.98	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			921.8	73.94	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			1272.9	89.44	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			1790.9	104.6	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			2607.3	130.7	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			3502.7	160.2	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			5223.3	214	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			7014.2	270.7	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			8769.9	326.5	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			10578	389.1	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			12290	457.8	25	120.6	0	95		931.95		179	1.03		68		4.267	4.877	0.559	1.016	0.238	0.192
			395	57.05	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			772.5	72.9	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			921.8	79.35	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			1185.1	92.49	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			1738.2	109.2	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			2616.1	139.7	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			3467.6	163.9	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			5276	205.1	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			7023	246	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			8778.7	288.1	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			10482	334.4	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			12299	383.6	25	157.7	0	95		931.95		179	1.03		68		0.457	4.877	0.254	1.016	0.095	0.192
			403.8	55.14	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			755	68.71	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			965.7	74.52	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			1255.4	83.53	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			1790.9	98.62	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			2695.1	114.81	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			3520.3	133.1	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			5223.3	167.4	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			7005.4	201.3	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			8752.4	236.8	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			10429	265.5	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192
			12290	317.2	25	163.8	0	95		931.95		179	1.03		68		0.305	4.877	0.254	1.016	0.081	0.192